Function to Functional: Investigating the Fundamental Human, Environmental, and Technological Factors Affecting the Mobility of Visually Impaired People

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PhD Thesis

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Declaration of Originality

I hereby declare that I have personally carried out the entire work described in this thesis. Where sources of information or the work of others have been used, they are fully cited and referenced and / or with appropriate acknowledgement given.



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Abstract

A detailed understanding of the mobility of visually impaired people is critical to the advancement of universal design and assistive technology. In turn, this enables visually impaired people to carry out activities of daily living, facilitating societal integration. To date, there exists a significant gap in this, with the consequence of an incomplete understanding of mobility requirements. This thesis addresses this challenge through a mixed-methods approach including in-depth literature review, practical experimentation, and quantitative and qualitative analysis. The novelty, rigour, and impact of this work is presented through a holistic framework of metrics influencing visually impaired mobility, including requirements. This comprises human, environmental, and technological factors expanded through crowd dynamics experimentation with visually impaired people, and a thematic analysis identifying challenges and coping mechanisms in different environments. Aided by subject-matter experts, the requirements are implemented, tested, and validated in a navigation system for visually impaired people. This paves the way for evidence-based policy making, technological development, and the uncompromised autonomy of visually impaired people.

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List of Abbreviations

ADA	Americans with Disabilities Act
AMD	Age-Related Macular Degeneration
ANEC	Association for the Coordination of Consumer Representation in Standardisation
ANED	Academic Network of European Disability experts
AOA	Angle of Arrival
API	Application Programming Interface
ARM	Age-Related Maculopathy
AVAS	Acoustic Vehicle Alerting System
B	Blind
BEMS	Binary Electronic Mobility System
BL	Bluetooth
BLE	Bluetooth Low Energy
BRISK	Binary Robust Invariant Scalable Keypoints
BS	British Standard
CCT	Correlated Colour Temperature
COP	Check on Progress
CS	Contrast Sensitivity
CV	Coefficient of Variation
CVI	Certificate of Visual Impairment
CVL	Central Vision Loss
DfT	Department for Transport
DNN	Deep Learning and Neural Networks
EKF	Extended Kalman Filter
EOA	Electronic Orientation Aid
ETA	Electronic Travel Aid
EU	European Union
GA	Geographic Atrophy
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMD	Head-Mounted Display
HRD	Hereditary Retinal Diseases
ICC	International Code Council
ICF	International Classification of Functioning, Disability and Health
IMU	Inertial Measurement Unit
IPS	Indoor Positioning System
LED	Light-Emitting Diode
LCA	Leber Congenital Amaurosis
LRV	Light Reflectance Value
MBN	Mobile Blind Navigation
MOODS	MoBIC Outdoor System
MOPS	MoBIC Pre-journey System

NSP	Normally Sighted Participant
O&M	Orientation and Mobility
OCR	Optical Character Recognition
ORR	Office of Rail and Road
OTA	Over-The-Air
PAMELA	Pedestrian Accessibility Movement Environment Laboratory
PNT	Positioning, Navigation and Timing
POI	Points of Interest
PSD	Platform Screen Doors
PV	Peripheral Vision
PVL	Peripheral Vision Loss
PWS	Preferred Walking Speed
PPWS	Percentage Preferred Walking Speed
PRM	Person with Reduced Mobility
RIN	Royal Institute of Navigation
RNFT	Retinal Nerve Fibre Layer
RNIB	Royal National Institute of Blind People
RP	Retinitis Pigmentosa
RTLS	Real-time Locating System
RV	Raised-Visual
RVAR	Rail Vehicle Accessibility Regulations
SD	Standard Deviation
SFAD	Standards for Accessible Design
SIFT	Scale-Invariant Feature Transform
SI	Sight Impaired
SLAM	Simultaneous Localisation and Mapping
SME	Small or Medium-sized Enterprise
SOOP	Signals of Opportunity
SS	Sensory Substitution
SSI	Severely Sight Impaired
SURF	Speeded Up Robust Features
SWAN	System for Wearable Audio Navigation
TDOA	Time Difference of Arrival
TfL	Transport for London
TTS	Text to Speech
TUAG	Turn Up and Go
UFV	Useful Field of View
UK	United Kingdom
UKRI	UK Research and Innovation
USB	Universal Serial Bus
UWB	Ultra-wideband
VA	Visual Acuity
VF	Visual Field
VIP	Visually Impaired Participant
VIPDR	Visually Impaired Pedestrian Dead Reckoning
VLC	Visible Light Communication

VO	Visual-Only
WHO	World Health Organisation

1. Introduction to the Mobility of Visually Impaired People

This chapter introduces the thesis, its aims and objectives, and its structure. Section 1.1 commences with a background on accessibility and the mobility of disabled people. This is followed by section 1.2 where this research's aims and objectives are described. Finally, section 1.3 summarises the thesis' structure.

1.1. Background to Accessibility and the Mobility Disabled People

1.1.1. Interactions of Mobility, Accessibility, and Disability

Mobility and accessibility are fundamental factors in enabling an individual to carry out activities of daily living. In turn, this becomes integral to social and urban integration by enabling access to private and public services, and their assets (Colleoni, 2013; Preston & Rajé, 2007). Modern engineering should therefore ensure that users with a broad range of abilities, operating within the widest possible range of situations, receive equal opportunities to access and benefit from such services, products, or environments. Indeed, this is the principle behind universal design, an architectural philosophy that ensures inherent accessibility in a system for users with and without a disability (Mace et al., 1997).

It is therefore important to first define mobility, accessibility, and disability, with an understanding of their interdependencies in the context of engineering and systems design. Mobility and accessibility are two different concepts. Mobility can describe the way in which an individual human moves within their environment, such as a transit network or a streetscape. (Keyfitz, 1973). The mobility of an individual is therefore typically described as an individual's freedom of movement and, in real-life mobility performance, is a function of a multitude of physiological, psychological, and environmental factors. These are often complex and may not reflect mobility capacity as tested in laboratory settings (Giannouli et al., 2017; Giannouli et al., 2016).

Accessibility, in its simplest definition, pertains to the ability to access, use, and benefit from a product, service, or environment. As described by Iwarsson and Ståhl (2007), accessibility should be considered in a composite approach that considers both the access requirements of the individual (based on their ability) and the accessibility provisions within the product, service, or environment that is to be accessed. This is not to be confused with 'usability', which refers to the effectiveness of utility of a product, service, or environment in achieving a user's goal. The more extensive coverage of a system's performance through its usability, rather than in its accessibility, can be argued to be a more realistic metric of system performance (Iwarsson and Ståhl, 2007).

The term 'disability' can be broadly defined as a disadvantage or handicap. English Law recognises and imposes the definition provided by Section 6 of the Equality Act (2010), which identifies a disabled person as possessing the following characteristics:

a) The person has a physical or mental impairment, and
b) The impairment has a substantial and long-term adverse effect on the person's ability to carry out normal day-to-day activities.

Disabilities can fall under several categories and severities, as described by the International Classification of Functioning, Disability and Health (ICF) (World Health Organisation, 2002).

The ICF also includes a list of environmental factors. For instance, specific learning disabilities (SLD), speech or language impairments, and visual impairments, including blindness, are diverse disabilities that could have drastically varying impacts on one's livelihood and perception of the surrounding environment (World Health Organisation, 2002).

As a result of varying ability and the arising, sometimes complex, accessibility requirements of disabled individuals, significant variance can exist in the mobility of different individuals and social groups. Such is propagated by factors including, but not limited to, unfamiliar environments causing reduced confidence, physical impairments reducing walking ability, and inaccessible designs (such as doorways) acting as mobility barriers (Boyce et al., 1995a; Boyce et al., 1995b; Boyce et al., 1995c). These collectively and ultimately lead to restrictions on the use of services, societal segregation, and an overall reduction in quality of life (Colleoni, 2013). Improving quality of life through enhanced accessibility for disabled users, thereby improving their mobility within their environment, has become of substantial focus in engineering and technology. Indeed, this is an integrated approach, as required by performance-based codes; characterizing occupants and characterizing their environments are not mutually exclusive activities (Boyce et al., 1999a).

This may arise from policy making in transportation systems (Preston & Rajé, 2007; Transport for London, 2016; Transport for London, 2002), infrastructure design through improved standards (Great Britain. Office of Rail and Road, 2010; ANED, 2013; United States. Department for Justice, 2010), and the development of assistive technology to enhance individual ability, such as the white cane, Electronic Travel Aids (ETAs) and optical scene detection systems for visually impaired people (United States National Research Council, 1986; Blasch et al., 2010; Foong et al., 2011; Wang & Tian, 2012).

1.1.2. Operational Scenarios – From Daily Activity to Emergency Egress

It is difficult to quantify the mobility performance of an individual. A challenge arises in that humans typically operate in different environments on a daily basis, with the potential to quickly transition between them. For instance, one may travel from a private dwelling through to a congested streetscape, utilising public transit services to arrive at a workplace. While this appears a routine journey, numerous uncertainties arise, including congestion and crowd behaviour on the journey, service suspensions on transit networks, or an emergency scenario.

A familiar journey can thus rapidly transition into one with unfamiliar impacts on the mobility of the individual, compounded by the unique abilities of that individual. In the study of human behaviour, it is therefore important to consider the individual and the dynamics of the environment in which they operate, observing such factors as crowd dynamics, route familiarity, and the potential of unexpected events such as an emergency evacuation (Bellomo et al., 2016a; Bellomo et al., 2016b; Wijermans et al., 2016).

An emergency evacuation is the urgent movement of people away from an area containing a risk to life or property, such as in a fire (Abrahams, 1994). Hindrances to the rate of evacuation must therefore be minimised, given that such events could cause mortalities and significant economic losses. For instance, in 2015/16, 7,661 casualties in fires and 303 fire related fatalities were recorded in England (Smalldridge, 2017). Being overcome by gas and smoke was noted as the most prevalent cause of death in fire related fatalities (Smalldridge, 2017).

An important factor in the safe egress of a person is their ability to independently mobilise. Indeed, disabled persons typically yield poorer evacuation performance as a result of reductions in this capacity (Boyce et al., 1999b). Whilst studies to facilitate improved environmental accessibility and egressibility for disabled users have been conducted, such as the development of evacuation elevators (Ronchi & Nilsson, 2013) and the evacuation chair (Hunt et al., 2013), the current understanding of the fundamental human factors associated with a disabled person's evacuation remains insufficient (Christensen & Sasaki, 2008). Moreover, whilst evacuations involving disabled users have been monitored, such as that by Proulx (1995), most have failed to reliably separate the effects of physiological and psychological factors on the evacuees involved, both individually and within their interactions in crowds.

1.1.3. Additional Challenges for Visually Impaired People

To become independent, the 'user' within a particular environment must be able to fully appreciate their orientation in the space around them. A loss of spatial orientation will lead to a loss in autonomy. This is a problem that affects users with and without a visual impairment; however, a solution is more difficult to obtain for users with a visual impairment. This is because a reduction in sight hinders the ability of visually ordering the physical environment via the full use of visual memory (Sanchez & Maureira, 2007).

Visual impairments also have a large variety of manifestations, affecting different metrics of sight by greatly varying proportions. These include visual acuity, visual field, contrast sensitivity, and colour vision (Cline et al., 1997; Spector, 1990; Pelli & Bex, 2013; Sharpe et al., 1999), Design issues for engineers seeking equal accessibility in the built environment are therefore further augmented when considering the needs and capabilities of users with wide-ranging visual impairments (Feghali, 2018).

Those with a visual impairment are therefore more susceptible to reductions in mobility. This leads to inaccessibility and elevated risk in several operational environments, including emergency scenarios. These may result from, but are not limited to, inabilities to detect signage (Boyce et al., 1999d), poor wayfinding, obstacle detection, and lack of confidence (Wright et al., 1999; Samoshin & Istratov, 2014; Feghali, 2018), and logistical limitations in identifying and deploying evacuation protocols (London Fire Brigade, 2007).

Additionally, the psychological effects of discriminating the surrounding environment through sight are complex. Giannouli et al. (2017) describe how mobility performance correlates with cognition, specifically in the visuospatial attention of the individual. Additionally, Ulrich (1979) describes that the visual detection of nature scenes provided greater emotional well-being than urban scenes which, instead, aggravated feelings of sadness and aggression. Such complexity is furthered by the disturbance of visual processing in visually impaired people. Moreover, these behaviours compound with physiologically-driven impairments to mobility and the ability to carry out daily activities (Freedman et al., 2002; Himann et al., 1988; Boyce et al., 1999b; Welage & Liu, 2011).

1.2. Aims and Outcomes of this Research

To address the human, environmental, and technological challenges impacting the mobility of visually impaired people, an understanding of these factors must first be attained. The aim of

this research is to therefore deliver a holistic understanding of the metrics influencing the mobility of visually impaired people. In turn, this allows for the development and validation of a user requirements framework for visually impaired mobility. Tangible benefits to the development of effective accessibility design and assistive technology can then proceed.

This, however, is a multi-disciplinary and complex process with several interlinking phases. A mixed methods approach including critical literature review, practical experimentation (quantitative mobility testing), and thematic analysis based on semi-structured interviews (qualitative data collection) with visually impaired people is proposed. The objectives of this research are therefore to:

- Assess current behavioural modelling practices to identify the overarching process of describing visually impaired mobility, including mobility capacity (human factors), mobility performance (environmental and technological factors), and their relationship.
- Identify and understand different visual impairments and their impacts on a person's sight to correlate the human health factors associated with sight and mobility.
- Critically investigate the state-of-the-art of visually impaired mobility capacity to detail causal factors, and their measurement in existing medical and engineering research.
- Devise and execute an appropriate methodology, where shortcomings arise, to collect quantitative and qualitative data on the mobility capacity of visually impaired people.
- Determine the state-of-the-art of environmental and technological augmentations in visually impaired mobility performance, and their shortcomings.
- Consolidate all findings from mobility capacity and mobility performance, including experimental findings, to devise a framework of user requirements for visually impaired mobility.
- Utilise mixed methods to address literature gaps in visually impaired mobility performance.
- Validate requirements through their contribution to the development and testing of a mobility aid for visually impaired people. This represents the holistic applicability of this thesis, from the fundamental derivation of human factors to their validation through system development and testing.

1.3. Thesis Structure

In following its objectives, the thesis begins by investigating the fundamental human factors affecting visually impaired people (mobility capacity), then transitioning to the investigation of environmental and technological factors (mobility performance). Finally, the framework of requirements is created and validated through practical implementation.

Chapter 1 introduces the thesis by providing background on the research topic, research aims and objectives, and the thesis structure. Chapter 2 begins with a literature review to determine the complexities of human behaviour analysis, and the process for determining mobility capacity, mobility performance, and their relationship. The implications of visual impairment on visual function are then listed, forming the critical first step of describing the visually impaired person. An important finding is that both individual and crowd behaviour must be investigated when determining human factors. Chapter 3 then proceeds to the derivation of mobility capacity, investigating physiological and psychological human factors experienced by

the individual operating on their own and in a crowd. A critical literature gap is found in the measurement of these factors, and in the current understanding of how visually impaired people behave in crowds.

Chapter 4 describes the steps forward following these discoveries, including the preposition of practical experimentation to address them. Subsequently, Chapter 5 conducts experimentation to discover the behaviours of visually impaired people in unidirectional and opposing crowd flows. The results of this experiment are analysed and summarised. Given a novel understanding of mobility capacity, Chapter 6 proceeds to derive factors influencing mobility performance through critical literature review. This includes environmental augmentation, assistive technology, and their standards and shortcomings. Two critical literature gaps are identified; the first is that existing mobility tools do not exhaustively address visually impaired mobility needs, resulting from unavailability of user requirements, or limitations in the underpinning technology. The second is that challenges experienced by a visually impaired person in different environments have not been sufficiently detailed in literature.

Chapter 7 consolidates all prior findings to define a novel framework for the user requirements of visually impaired mobility. Chapter 8 then discusses the contribution of these requirements in the design, development, and validation of a navigation solution for visually impaired people. Chapter 9 conducts semi-structured interviews (including thematic analysis) with visually impaired people to understand the challenges experienced in different environments. Both literature gaps in mobility performance are therefore extensively investigated. The thesis concludes by summarising the research aims and objectives, and conclusions arising through addressing them. This includes limitations and future work. The structure of this thesis is graphically represented by Figure 1.1.



Figure 1.1: Overview of report structure.

2. Understanding and Identifying Challenges in Modelling Human Behaviour and Classifying Visual Impairment

This chapter studies behavioural modelling practices to identify the overarching process of describing visually impaired mobility, including mobility capacity (human factors), mobility performance (environmental and technological factors), and their relationship. Different visual impairments and their impacts on a person's sight are then observed. This produces the foundations of mobility analysis for which proceeding chapters will explore in detail. Section 2.1 commences by describing the literature review methodology, the principles of which are applied throughout the literature reviews within this thesis. Section 2.2 proceeds to observe the fundamental challenges of human behaviour modelling. The importance of investigating individual and group behaviour in capacity and performance is discussed here. Visual impairment and its functions are reviewed in Section 2.3. The classification and prevalence of such are then described in sections 2.4 and 2.5, respectively.

2.1. Literature Review Methodology

The literature review methodology employed throughout this thesis is one with a systematic approach, applied consistently throughout the research objectives. The aim is to create an unbiased and comprehensive review of all available research. This involves research directly investigating the mobility of visually impaired people, or indirectly proposing how visual impairment can lead to changes in human behaviour and, thus, mobility. While a meta-analysis would have been ideally conducted, it becomes clear that the research methodologies employed by the collected research vary significantly in the sample size tested, the characteristics of testing groups, the environments tested, and the type of data collected. Intuition is therefore necessary to deliver realistic and feasible conclusions. For instance, research studies are referenced to indicate that visual field can affect mobility, but an exhaustive literature review on how visual field can affect mobility is not conducted. This is given either a lack of existing research into this specific factor, or that studies reviewed do not allow for fair comparison.

Firstly, a review into general modelling theory and the complexity of human behaviour is conducted. This defines the scope and complexity of the research that will need to be conducted, as well as the significance of a multi-scale approach to the validity of this research. Medical research papers are then reviewed to obtain a better understanding of the different functions of sight and visual impairment. This includes reviews of local and global surveys to assess the manifestations of visual impairment with age and mobility.

A broad investigation into the mobility characteristics of visually impaired people then proceeds, defining the different operational scenarios in which these may differ. It is noted that the mobility capacity of visually impaired people could be discretised into physiological and psychological factors. These are further divided into an individual interaction and a group interaction, then categorised by the operating environment, type of visual impairment, and the use of additional mobility tools. The sheer scope of variables that could impact a visually impaired person's ability to mobilise in an environment is highlighted.

A methodical literature review for each factor is carried out concurrently, aiming to identify currently understood interactions between variables and shortcomings in the research thus far.

This involves studying the characteristics posed by different pedestrian flows and empirical environments. Expansion to include realistic environments then follows, reviewing literature pertaining to visual, auditory, and tactile augmentations. Simultaneously, the development of mobility aids in literature is reviewed, observing the interaction of the human and environmental factors that are revealed as the literature review progresses. These findings convolve in the requirements framework for visually impaired mobility and are referenced throughout the proposal of experimentation and validation throughout this thesis.

2.2. Fundamental Challenges of Understanding and Augmenting Human Behaviour

2.2.1. Modelling Human Behaviour

The predictive modelling of human behaviour can be used to influence and improve engineering and accessibility design (Bellomo et al., 2016a). Therefore, significant research has been devoted to creating and refining such models. However, credible validation is pivotal to reliable practical applications (Wijermans et al., 2016). This is particularly critical as models aim to predict complex human behaviours, many of which remain misunderstood and with little data to accurately define and recreate (Bellomo et al., 2016b). Moreover, environmental conditions can also account for large deviations in a model's outputs. For instance, these can include the width of corridors, the positioning of doorways, and the visual and auditory reference points presented to the subjects being modelled (Daamen & Hoogendoorn, 2012).

2.2.2. Group Behaviour and the Multi-Scale Approach

The study of human crowds is an interdisciplinary research field which presents significant computational and complexity challenges (Bellomo et al., 2016a). Indeed, a crowd presents a 'living system', where complex interactions between individuals surmount to new physical and psychological behaviours (Bellomo et al., 2016a).

For instance, public self-awareness reflects an individual's concerns regarding how others evaluate them, whereas private self-awareness approximates to objective self-awareness, monitoring the extent to which one's behaviour matches one's internal standards (Carver & Scheier, 198; Fenigstein et al., 1975). A lack of public self-awareness leads to anti-normative behaviours, whilst a lack of private self-awareness causes a loss of access to internal standards, allowing a person to fall under external control. Crowd dynamics typically feature a balance of both behaviours, or can strip both away, leading to new social behaviours that can be very complex to predict (Reicher, 2002).

It is therefore important to consider both the individual and crowd when developing a realistic model of human behaviour. This is described by the 3 scales of modelling, defined as follows:

1. Microscopic: Individual identified entities with the overall state of the system being defined by individual parameters and positions (Helbing, 2001).
2. Macroscopic: System described by Gross quantities typically dependant on space and time. Quantities obtained by local averages of the microscopic state (Hughes, 2003).
3. Mesoscopic: Based on kinetic theory models – microscopic state of pedestrians still defined by individual position and velocity, but representation delivered by a suitable probability distribution over microscopic state (Bellomo, 2012).

An integrated and multi-scale approach to crowd modelling is therefore required, especially when attempting to represent the deviations of different behaviours from the small to the large-scale. These can include large unanticipated and irregular crowd motion, such as stop-and-go waves, that may stem from the actions of a small group of individuals within the crowd (Bellomo et al., 2016a).

In summary, literature is aware of the challenges associated with human behaviour modelling. It is suggested that individual-level (microscopic) behaviours can define significant crowd-level (macroscopic) phenomena (Bellomo, 2012; Helbing, 2001; Hughes, 2003). In conjunction, Wijermans et al. (2016) finds that validation is critical to reliable practical application. It can therefore be ascertained that a sufficient understanding of the individual is needed prior to simulating the intrinsically complex behaviour of a crowd. This can then be used to construct the user requirements within different realistic operating environments.

2.2.3. Human Behaviour Modelling Principles

The following are five approaches used in the field of pedestrian behaviour modelling:

1. Cellular automation: *Microscopic, Discrete*
2. Agent-based models: *Microscopic*
3. Social Force Model: *Microscopic, Continuous*
4. Particle swarm optimisation models: *Microscopic*
5. Queuing models: *Macroscopic*

2.2.3.1. Cellular automation

The pedestrian being modelled is represented by a cell state. This modelling principle was derived from vehicle flow simulation and was further enhanced to accommodate the complex behaviours observed in pedestrian flows (Blue & Adler, 1999). A benefit of cellular automation models is their computational efficiency and that pedestrian interactions within these models are based on intuitive and understandable rules. This is as this modelling discretely idealises the partial differential equations used to characterise fluid flows, thus allowing for the simulation of multiple flows with complex characteristics (Bak, 1996).

2.2.3.2. Agent-based models

This modelling principle operates by simulating the behaviours and interactions of multiple agents. Agents are defined by rule-based operations and act upon them, allowing for emergent behaviours to form (Niazi & Hussain, 2011). This is similar to cellular automation models, where macroscopic behaviours are derived from multiple microscopic interactions (Blue & Adler, 1999). Agent-based models therefore excel in that they can simulate individuals with non-linear behaviours characterised by thresholds, individual adaptation (memory), and heterogenous agent-interactions that can have network-wide effects (Bonabeau, 2002).

In these models, the agents are presumed to be acting in their best interest. In egress, this could include self-preservation via competitive interactions with other agents and an increased walking speed. Indeed, the agent's environment therefore forms an integral part of their decision-making, thus making this modelling principal more natural (Bonabeau, 2002). Moreover, as agent-based models do not rely on averages and allow for certain fluctuations to

be amplified, a better representation of heterogenous agents (such as visually impaired individuals) can be achieved (Bonabeau, 2002).

2.2.3.3. Social Force Model

The motion of pedestrians in a Social Force Model is described by internal motivations within each individual to achieve their own target, termed a 'social force' (Helbing, 1995). This differs from other models in that the motion of the pedestrian is therefore not directly dictated by the surrounding environment. For instance, in a model presented by Helbing (1995), the modelling variables include:

1. Acceleration towards desired velocity of motion.
2. Terms to dictate the distance the pedestrian keeps between others around them, as well as borders and obstacles.
3. Attractive effects, such as the desire to follow a route or reach a destination.

These terms are non-linearly coupled and are capable of a good reflection of the collective behaviours of pedestrians.

2.2.3.4. Particle Swarm Optimisation Models

A Particle Swarm Optimisation (PSO) Model operates much more macroscopically in comparison to the models discussed previously. Here, candidate solutions, termed 'particles', are collected in one population, termed a 'swarm' (Kennedy & Eberhart, 1995). Simple mathematic formulation is used to then position the swarm within the search-space (Zhang, 2015). For instance, in an evacuation application, the swarm is the body of pedestrians being evacuated and the search-space is the space being evacuated including all possible routes the swarm may follow. Particles are moved based on their best-known positions and the best-known position of the swarm. The movements of each particle will therefore combine to define the motion of the swarm, thus creating a model that continually iterates upon itself by querying all its variables. Whilst a solution is typically found, it is not guaranteed that it will be accurate; the iterative process may not necessarily reflect significant changes in microscopic behaviour that could alter the swarm's positioning.

2.2.3.5. Queuing Models

Queuing Models are based on the principles of queuing theory, a mathematical study of queues and waiting lines (Sundarapandian, 2009). These models are typically used to influence business decisions and project management. This is as they simulate the interactions of several users across complex queuing networks as they use a certain service. Such services can range from traffic management to telecommunications, though queuing models can also be used in the design of emergency evacuation plans (Smith, 1991). Indeed, by using state-dependant queuing models, Smith (1991) demonstrated the application of queueing models to capture the nonlinear effects of increased occupant traffic flow through emergency evacuation routes. Primarily, this application of queuing models can be used to simulate arrivals, departures, and waiting times experienced by evacuees, both in single and multiple pedestrian flows. Given the macroscopic nature of this model, the fundamental physiological and psychological impacts on

a visually impaired individual within the flow are likely to be averaged and therefore unrepresented by such a model.

2.2.4. Behaviours in Operational Scenarios and their Application to Realistic Modelling

An operational scenario is the interaction of a pedestrian and an environment through a series of events and motivations. As such, an operational scenario comprises of two interacting elements:

1. The environment and mobility aids (external decisions)
2. The pedestrian (internal decisions)

Fundamentally, human mobility can operate in several different environments with elements, augmentations, and aids within these environments that could cause different walking behaviours. This is in both individual and crowd movement. Hillnhütter (2021) conducted novel research to observe how such elements can be measured, opting to use head movement as an outcome measure. Video footage of 924 randomly selected pedestrians in 18 urban environments in four cities across Europe was analysed. Changing head movements were noted as pedestrians encountered 7 elements of walking environments comprising car presence, shops and services, social activity, enclosures, edges and facades, streetscape appearance, and greenery.

Two conclusions proceeded. Firstly, it was found that elements within a 'human scale' (the range at which human sense organs function best) triggered the most pedestrian reactions (through head movement deviation). This was a radius of five to six metres around the pedestrian. Secondly, visual variation in environmental features such as street furniture, greenery, and facades led to greater pedestrian stimulation, structuring the walking environment into segments with differing walking behaviours.

Hillnhütter (2021) is limited in that only fast walking and 'determined' pedestrians (over 90 steps per minute) were observed. Children, strollers, and impaired pedestrians were not observed. This reduced test sample introduces subjectivity in how Hillnhütter (2021) defines a visibility determined or unimpaired pedestrian (negating invisible disabilities). Furthermore, omitting a heterogenous population means that the behaviours of visually impaired individuals in encountering these environmental features remains uncertain. This is especially given that visual stimulation was a major factor in Hillnhütter's (2021) findings. Controlled weather conditions, walking surfaces, and the European location of observed footage leave further uncertainty as to how diverse international settings could affect walking. Maintaining the same locale, however, was useful in controlling the fairness of the study.

Hillnhütter (2021) remains relevant in setting a foundation for future research; in attempting to measure mobility capacity, ensuring controlled environmental elements is important in mitigating any unknown environmental impacts on mobility. In laboratory settings, visual stimulation can be controlled by presenting monotonous environments, while also considering environmental features (such as walking obstacles) at the small ('human') and large scale. Only then can the investigation of environmental elements pursue to understand how each element enhances or degrades mobility performance.

In conjunction with the pedestrian's environment and mobility aids, the pedestrian's (internal) motivations and ensuing actions complete the operational scenario. Fundamentally, motivations can range from purposeful to freeform, in turn leading to functional or recreational mobility (Davies et al., 2012). This is actively planned by the pedestrian and internal decisions may become influenced by external decisions (the environment itself). Operational scenarios can therefore involve a sequence of changing motivations, comprising of tasks (macroscopic phases) and subtasks (microscopic phases) where the pedestrian may need to acquire information, orientate, navigate, and transition between each task and subtask (Foltz, 1998).

Indeed, there exists a good understanding of an overarching and ongoing motivation of a visually impaired person, regardless of task and subtask, when mobilising in any environment. As is concurrent in several studies (Strothotte et al., 1996; Loomis et al., 2001; Feghali et al., 2021), this is that a visually impaired individual desires effective:

1. Obstacle and hazard awareness
2. Orientation and wayfinding ('Where am I?')

The factors that then influence the individual's capacity to achieve these (both individually and in a crowd) can be compiled (termed 'mobility capacity'). This is followed by relevant environmental and technological augmentations to support each principal motivation in realistic operational scenarios (termed 'mobility performance'). Concurrently to these two principal motivations, Feghali et al. (2021) summarises the three different categories of mobility aid that exist:

1. Electronic Travel Aids (ETAs) for obstacle detection and hazard awareness
2. Electronic Orientation Aids (EOAs) for orientation and wayfinding ('Where am I?')
3. Binary Electronic Mobility Systems (BEMS) that attempt to combine the benefits of both ETAs and EOAs.

Figure 2.1 summarises this process of understanding capacity and performance from these principal motivations, and how they then feedback into behavioural modelling.

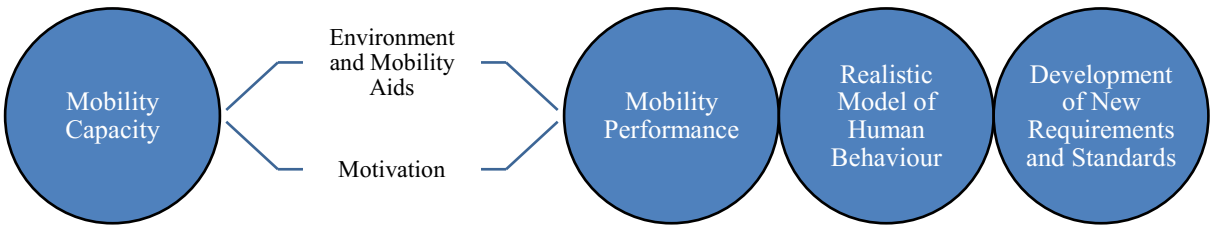


Figure 2.1: Transitioning from mobility capacity to the development of new requirements.

Evidence to contextualise motivations (tasks and subtasks) in visually impaired mobility through different environments remains largely anecdotal. This is especially when observing transitions between indoor and outdoor environments. Strothotte et al. (1996) conducted interviews of users and mobility trainers to determine visually impaired user requirements and assess mobility problems when travelling independently. The outputs of this were used to construct the MoBIC Pre-journey System (MOPS) to assist users in planning journeys, and the

MoBIC Outdoor System (MOODS) to execute these plans by providing users with orientation and navigation assistance during journeys. Users expressed internal motivations through a need to plan the journey at home, or prior to travelling. This included setting constraints on the planning of the route, such as the shortest or safest route. Moreover, navigation should dynamically change to ensure a safe route, such as avoiding congestion and clockwise crossings, thus showing impact of external factors on internal motivation.

The Wayfindr (2018) open standard, published in March 2018 as Version 2.0, is the only standard that has been published for indoor digital navigation service providers and venue owners. The aim of the standard is to overview the requirements of visually impaired individuals in navigating indoor spaces. It sets guidelines which navigation providers should consider within their solutions to meet them. As found in Strothotte et al. (1996), the open standard recognises different tasks and subtasks such as planning a journey, navigating to ticket machines in a train station, and understanding the platform layout. However, the standard is not comprehensive in the environments it considers and does not capture the effects of crowd interaction, high-stress scenarios (such as evacuations), and the user's existing knowledge.

In summary, research is needed to define the mobility requirements of visually impaired individuals operating individually and in a crowd in realistic operational scenarios (Strothotte et al. 1996; Wayfindr, 2018; Hillnhütter, 2021). This crucially requires a foundational and empirical understanding of the visually impaired individual's mobility capacity in individual and crowd motion through critical literature review (Chapter 3), novel experimentation (Chapter 5), and mobility performance under different environments and mobility aids (Chapter 6).

2.3. Fundamental Causes and Effects of Visual Impairment

2.3.1. Parameters of Sight and Classification of Visual Impairment

The nature and prevalence of visual impairment is first ascertained prior to discovering how such can affect the individual and, in turn, their behaviour in realistic operational scenarios. It is found that different parameters of sight, termed visual functions, constitute the biological performance of the 'organ'. These translate to impairments of the 'person' where, in combination, the functional vision of the visually impaired individual is formed. This defines the realistic impacts of their vision loss and their ability to undertake Activities of Daily Living (ADL) (International Council of Ophthalmology, 2002). The following figure (Figure 2.2) from the International Council of Ophthalmology (2002) outlines the process in which visual function can result in impacts on daily life.

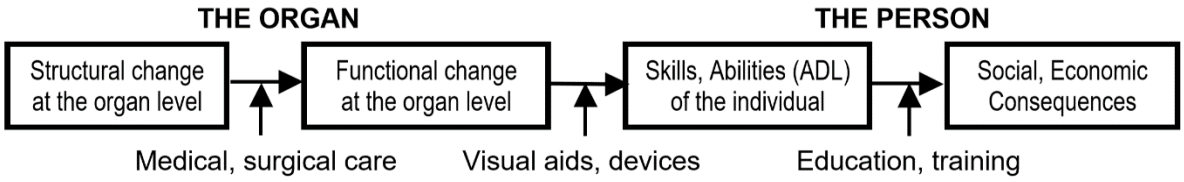


Figure 2.2: The process in which visual impairment can affect an individual on an organ and person-level (International Council of Ophthalmology, 2002).

It is therefore important to understand visual function and the methods in which it is quantified. This is especially as monocular visual function can vary extensively between each eye, forming

a complex composite binocular visual function. These amount to visual acuity (Leguire et al., 2011), visual field (Spector, 1990), and contrast sensitivity and colour vision (Vaegan et al., 1993). While each can vary independently with different visual impairments, there remain interdependencies between each function. Predictions pertaining to the general effect of a visual impairment on visual function can therefore be made (Vaegan et al., 1993; Pelli & Bex, 2013).

2.3.2. Visual Acuity

Visual acuity represents the spatial resolution of a person's vision and can simply be defined as the clarity of vision. It explains the ability of a person to resolve finer elements in their vision and is dependent on optical and neural processes. These are the fundamental health and performance of the retina within the eye, and the sensitivity of the cognitive faculty of the brain (Cline et al., 1997). Visual acuity is dependent on distance, with variations occurring between distance, intermediate and near visual acuity. Additionally, binocular acuity may differ from monocular acuity, with deviations occurring at different distances (Tsilimbaris et al., 2011).

A Snellen chart can be used to demonstrate and measure visual acuity (Snellen, 1862). The visually impaired patient is asked to sit 6 metres (20 feet) away from a chart with optotypes (letters of varying size) positioned as shown in the Snellen chart in Figure 2.3. The patient is then asked to read down the chart until no further optotypes can be reliably identified. The optotypes change across each unique chart, and patients may be tested monocularly or binocularly on different charts.

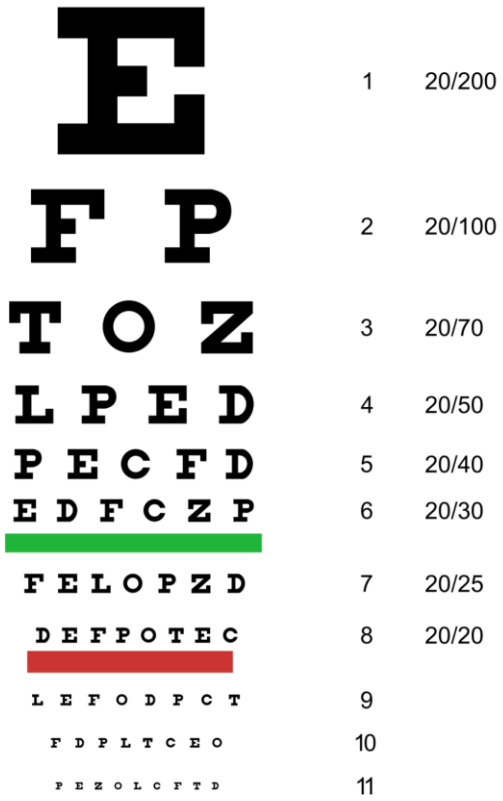


Figure 2.3: A Snellen chart used in the measurement of visual acuity (Snellen, 1862).

Visual acuity can be represented as a fraction as follows:

$$\frac{Distance\ Between\ Subject\ and\ Chart}{Distance\ at\ which\ Person\ with\ Normal\ Acuity\ Discerns\ the\ Same\ Optotype}$$

A value of 1 indicates normal acuity and is typically represented as 6/6 (metres) or 20/20 (feet). The numerator is fixed and changing acuity is represented by a varying denominator. Considering an acuity of 6/6, this states that, at 6 metres away, contours that are approximately 1.75 mm apart can be identified and separated. For example, in the Snellen chart in Figure 2.3, an acuity of 20/40 describes a visually impaired person that discerns an optotype at 20 m that a person with normal acuity can discern at 40 m. Therefore, a visually impaired person with 20/40 vision can be described as possessing half the spatial resolution as one with normal acuity. Twice the optotype size is then needed to discern it at that distance.

The clinical assessment of visual acuity is not limited to optotypes on a Snellen chart; other standard methods such as Landolt Cs, where patients must determine the orientation of a rotated 'C' optotype, can be used (Bondarko and Danilova, 1997). However, these methods may not exhaustively reflect the true visual acuity of an individual in different operational scenarios, such as in the presence of varying environmental illumination and contrast (Berman et al., 1993). Furthermore, as visual acuity varies by distance, it can be assessed for near distances, such as when reading a book, and far distances, such as when observing signage across a street (Sloan, 1959). Acuity is therefore not a comprehensive measure of visual function, and can vary independently to other functions according to external factors. For instance, 20/20 vision can be achieved by persons with glaucoma on acuity tests, yet these individuals may still struggle with daily activities, such as mobility in dim lighting (Leguire et al., 2011).

2.3.3. Visual Field

The visual field is a defined space in which objects are visible at the same instant whilst a continuous fixation is held in one direction (Spector, 1990). In optometry, ophthalmology, and neurology, testing of the visual field allows for determination of diseases that impact the visual field. This could be scotoma (an area of partial alteration of the visual field) or more extensive degeneration of sight. Additionally, Smythies (1996) addresses the psychological definition of the visual field that arises from introspection experiments.

The visual field is defined in degrees from the central fixation point and can be divided into central and peripheral vision. Additionally, as with other visual functions, the binocular (total) visual field is defined by the performance of each eye in their monocular visual field. Monocularly, central vision is represented by the inner 30 degrees of vision and peripheral vision refers to the broad range of points in the visual field that lie outside central vision. The normal monocular visual field typically extends 60 degrees upwards and 75 degrees downwards from the horizontal axis of central fixation, and 100 degrees laterally (away from the nose), and 60 degrees medially (towards the nose) from the vertical axis of central fixation (Spector, 1990). This is illustrated in Figure 2.4.

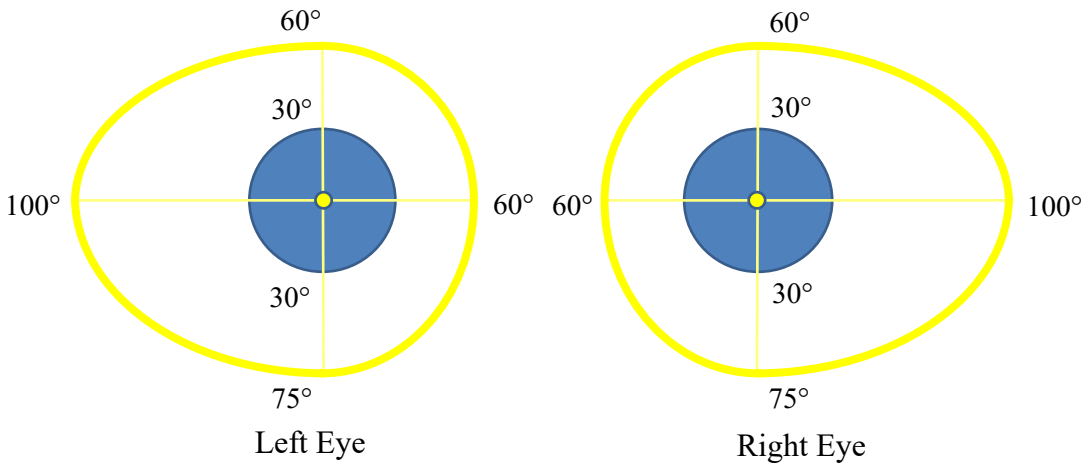


Figure 2.4: Illustration of the monocular visual field for each eye.

Acuity increases from an ability to discriminate movement in the extreme peripheral vision to a maximum in the central vision (Spector. 1990). Binocularly, the monocular fields combine, and the area for the left eye to the left of the vertical meridian at the centre of the visual field becomes the left visual field (temporally for the left eye and nasally for the right). The area for the right eye to the right of the vertical meridian at the centre of the visual field becomes the right visual field (temporally for the right eye and nasally for the left). The areas delimited by the intersection of the vertical and horizontal meridians of the visual field are quadrants termed by their position. Specifically, these are the superior (upper) and inferior (lower) left/right quadrants. This is highlighted in Figure 2.5 (Purves et al., 2001),

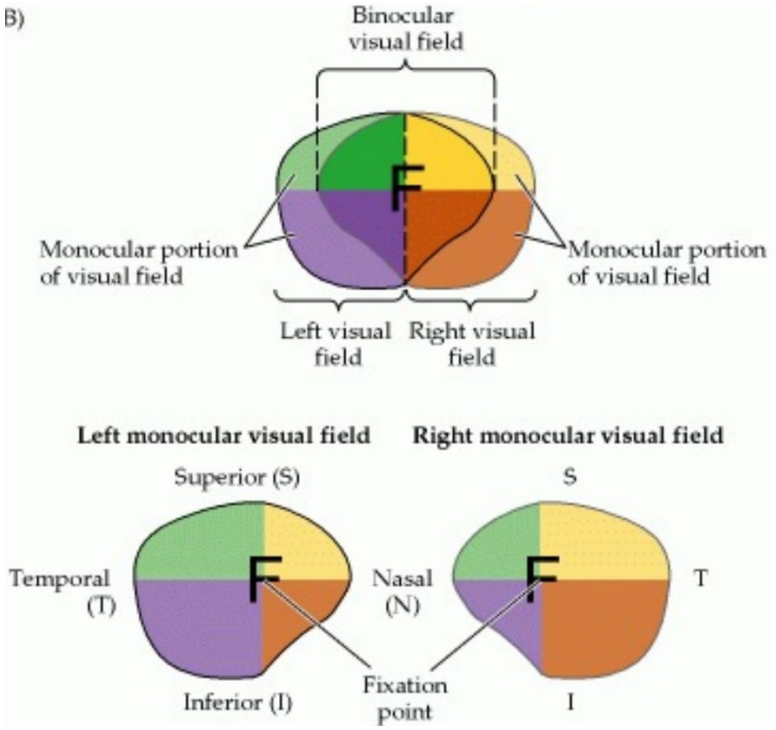


Figure 2.5: Illustration of the binocular visual field as a combination of the monocular visual fields (Purves et al., 2001).

Several ophthalmic and neurological conditions can cause alterations to the visual field. Diseases including Age-Related Macular Degeneration (AMD) and macular hole affect the

macula of the retina (encompassing a central 10 to 17 degrees in the visual field), causing such defects (Acton et al., 2012). These include Metamorphopsia, which distorts vision (Hartnett & Steidl, 2003), and central scotomas, which are interruptions of the visual field within its centre (Acton et al., 2012). Glaucoma causes several defects of the visual field through damage to the Retinal Nerve Fibre Layer (RNFT).

As with AMD, such defects change with the progression of the disease, with many occurring in the central visual field. These include generalized depression where the central and peripheral fields are mildly constricted, scotoma with varying severity (Khurana, 2019), peripheral field defects, and tubular vision (Hall et al., 2001; Artes et al., 2005). Other ophthalmic conditions including retinal detachment, cataract, visual pathway lesions (Khurana, 2019), and Hereditary Retinal Diseases (HRDs) can cause significant defects to the visual field.

For instance, Leber Congenital Amaurosis (LCA) is a HRD that causes retinal dystrophy. It can lead to severe impairment of peripheral vision, leaving only narrow tubular vision (Kumaran et al., 2017). Neurological conditions causing field defects include periventricular leukomalacia (Kozeis, 2010) and cerebral palsy (Black, 1982). Field defects can also occur following temporal lobe surgeries undergone by patients with epilepsy (Manji & Plant, 2000).

2.3.4. Contrast Sensitivity and Colour Vision

2.3.4.1. Contrast Sensitivity

A notable understanding of everyday visual performance can be obtained by testing a user's contrast sensitivity; it dictates their ability to detect stimuli of different colour under various lighting conditions. Vaegan et al. (1993) conducted trials using 15 subjects aged in each decade to age 80, totalling 120 subjects. In normally sighted participants, a small peak in sensitivity at 20–30 years of age was noted, but ultimately, contrast sensitivity was stable until about age 50 after which losses first appeared at the highest spatial frequencies tested (4.8 cy/deg). It was concluded that these changes could be psychological rather than optical.

Pelli & Bex (2013) conducted a review on how contrast sensitivity is measured, finding that reductions in contrast sensitivity can be observed in many clinical conditions. This includes those in which other parameters of sight, such as visual acuity, measure as normal. Additionally, reductions in contrast sensitivity can occur in both ophthalmic conditions and neurological conditions, as well as from the use of some prescription drugs (Santaella & Fraunfelder, 2007). The ophthalmic conditions reviewed by Pelli & Bex (2013) in which contrast sensitivity is hindered include AMD (Kleiner et al., 1988), glaucoma (Stamper, 1984), myopia (Collins & Carney, 1990), glare (Abrahamson & Sjöstrand, 1986), cataract (Hess & Woo, 1978), amblyopia (Freedman & Thibos, 1975), ocular hypertension (Gandolfi, 2005), and dry eye (Rolando et al., 1998).

The neurological conditions in which contrast sensitivity can be affected, as reviewed by Pelli & Bex (2013), can include multiple sclerosis (Regan et al., 1981), Parkinson's disease (Bodis-Wollner & Onofrj, 1993) and schizophrenia (Cimmer et al., 2006). This suggests that an individual without a clinically diagnosable ophthalmic condition should not be dismissed from the operational requirements of those with a visual impairment. This is especially given the additional implications on a person's cognitive and physical capabilities arising from neurological conditions or drug-use.

2.3.4.2. Colour Vision

Vaegan et al. (1993) explains that colour vision and contrast sensitivity are typically well-correlated, with reductions in contrast sensitivity leading to greater difficulty in differentiating between colours. Normal colour vision is Trichromatic; colours are reproduced from the combination of three primary colours, red, green, and blue. Congenital colour vision deficiencies arise from mutations of the cone photoreceptors in the eye, and are classified by severity, as summarised in Table 2.1 (Simunovic, 2009; Sharpe et al., 1999; Went & Pronk, 1985; Judd, 1943).

Deficiency	**Cones Affected**	**Prevalence (%)**
Anomalous trichromacy		
Protanomaly	Red	1.08
Deuteranomaly	Green	4.63
Tritanomaly	Blue	0.2
Dichromacy		
Protanopia	Red	1.01
Deuteranopia	Green	1.27
Tritanopia	Blue	0.2
Monochromacy		
Green-cone monochromacy	Red and Blue	<0.0001
Red-cone monochromacy	Green and Blue	<0.0001
Blue-cone monochromacy	Red and Green	0.001
Rod monochromacy and incomplete achromatopsia	Red, Green and Blue	<0.002

Table 2.1: Classification and prevalence of colour vision loss (Simunovic, 2009; Sharpe et al., 1999; Went & Pronk, 1985; Judd, 1943).

The least severe form of colour vision loss is anomalous trichromacy. As with normal vision, the combination of the three primary colours is still used to detect and classify colour. However, the way in which this occurs in those with anomalous trichromacy is atypical to those with normal vision, leading to differently accepted colour matches. The most prevalent forms of anomalous trichromacy affect the red (protanomaly) and green (deuteranomaly) cones (Sharpe et al., 1999). Those with anomalous trichromacy may have colour vision that approaches that of normal vision (Baraas et al., 2010) or a total loss in the ability to detect the faulty colour.

Dichromacy is a more severe form of colour vision loss with a typically lower prevalence than anomalous trichromacy (Sharpe et al., 1999). Here, only two primary colours can be used to discriminate colour and, similarly to anomalous trichromacy, the affected cone is described by protanopia (red), deuteranopia (green), and tritanopia (blue). Other reductions in visual function may be observed under dichromacy, including moderate acuity reduction, moderate to high myopia, and astigmatism (Michaelides et al., 2005).

Monochromacy is the most severe form of colour vision loss and the least prevalent (Sharpe et al., 1999; Judd, 1943). Here, colour discrimination is lost, although residual colour discrimination may be observed. In very rare instances of monochromacy, termed cone monochromacy, normal visual acuity may prevail. However, in the more common rod monochromacy, the dysfunction of the cones is so severe as to cause significant reduction in other visual functions. This is as the rods in the retina, responsible for night vision, dominate

visual function (Simunovic & Moore, 1998). Impairments can include poor visual acuity, nystagmus, and abnormal response and sensitivity under photopic conditions (Simunovic & Moore, 1998).

2.3.5. An Important Consideration on Visual Function and its Measurement

It is important to note that, following this review of visual function, it is unlikely that causes of visual impairment will have a singular impact on one parameter of sight. Rather, visual impairments show complex manifestation on visual function. For example, conditions leading to retinal dystrophy cause reductions in all parameters, especially contrast sensitivity and peripheral vision (Kumaran et al., 2017). Other conditions such as AMD cause reductions in central vision and visual acuity (Kumaran, 2008). It was noted that these findings derived from relatively varied experimental samples. For instance, Vaegan et al. (1993) tested 120 subjects and Leguire et al. (2011) tested 13 subjects. Notwithstanding this, it was consistently observed that, even within samples of similar visual impairment causes, significant variances in sight remained.

Moreover, there remains uncertainty as to how measurement technique, including apparatus used, monocular versus binocular, and clinical environment, impact measured visual function and its predictability of mobility (Haymes et al., 1994; Genensky et al., 1979). Haymes et al. (1994) argues that measurements of function are only applicable to the prediction of mobility if they are conducted under the same conditions as any mobility testing. This is supported more broadly by Genensky et al. (1979) where it was argued that clinical measures of function are inappropriate for conclusive real-world predictions of functional vision.

2.4. Classification of Visual Impairment in Research

2.4.1. Classification of Visual Impairment by ICD-11

According to the World Health Organisation (WHO) in the International Classification of Diseases (ICD) Version 11 (ICD-11) (World Health Organisation, 2018), visual impairment can be classified into distance and near acuity impairments (considering the better eye) with different categories of severity. This is shown in Table 2.2.

Classification of Visual Impairment	Visual Acuity Worse Than
Distance – Mild	6/12
Distance – Moderate	6/18
Distance – Severe	6/60
Distance – Blindness	3/60
Near Vision Impairment	N6 or M.08 with existing correction

Table 2.2: Classification of visual impairment severity according to ICD-11 (World Health Organisation, 2018).

The investigation of visually impaired mobility should access reliable guidance on what constitutes and discretises the severity of visual impairment. Such allows for studies of visually impaired mobility to present comparable data based on similarly discretised experimental samples. That is, for instance, that two studies utilise the same definition of ‘severe visual impairment’ to identify those considered to be severely visually impaired in their testing sample. The classification presented by the WHO (2018) acts as a global standard and should therefore provide a rigorous and reliable frame of reference for such research.

Dandona and Dandona (2006) identified three issues arising from a previous version of the ICD, only the third of which has been rectified in ICD-11. Firstly, it is noted that the definitions provided pivot around best-corrected visual acuity. This excludes uncorrected refractive errors and, as reasoned by Dandona and Dandona (2006), leads to a substantial underestimation of approximately 38% of the total burden of visual impairment. Secondly, distance blindness is represented as an acuity worse than 3/60, whereas it is argued that increasing human development leads to greater visual acuity requirements. This justifies a cut-off of 6/60 to represent blindness. Thirdly, and as has now been rectified in ICD-11, the prior use of the term 'low vision' to identify any visual impairment that is not blindness should be revised to use alternative terms. This avoids confusion with non-correctable vision requiring aids or rehabilitation, as commonly defined through 'low vision'. The grading system in ICD-11 is similar to that proposed by Dandona and Dandona (2006).

However, the revisions presented in ICD-11 and Dandona and Dandona (2006) are limited in that visual acuity remains the primary indicator of visual impairment severity. Consequently, the dynamic impact on visual function by visual impairments is not considered. Effectively, the realistic visual acuity of an individual can change given their operational scenario. Such may not be comprehensively captured in standardised laboratory testing of visual acuity. ICD-11 (World Health Organisation, 2018) only states the following in addition to the classification of visual impairment through visual acuity:

> 'For characterizing binocular vision impairment, vision acuity should be measured with both eyes open with presenting correction if any. For characterizing monocular visual impairment, visual acuity should be measured monocularly with presenting correction if any.
>
> If the extent of the visual field is taken into account, patients with a visual field of the better eye no greater than 10° in radius around central fixation should be placed under 'inocular'. For monocular blindness, this degree of field loss would apply to the affected eye.'

Instead, a combination of visual function testing in different environments is necessary. Indeed, Tan et al. (1998) finds that, in patients with posterior capsule opacification, visual acuity was predictive of contrast sensitivity but a poor predictor of glare. Glare could be disabling, particularly in high-intensity lighting (Tariq et al., 2007). Kumaran et al. (2017) describes how patients with HRDs typically experience significant reduction in visual function in dim light, performing more poorly than their measured visual acuity may indicate.

This was demonstrated by Rubin et al. (2010), Black et al. (1997), Spark Therapeutics (2019), and Feghali (2018) where visually impaired participants yielded broadly varying performance in environments where light levels were varied. While not exhaustive, these examples evidence that the ICF-11 cannot be wholly relied on when discretising a visually impaired test sample. In the context of mobility testing, each visual function's variation may determine performance. This is explored in the proceeding literature review (Chapter 3) within this thesis.

As concluded by Dandona and Dandona (2006), classifications can be limited in that they do not consider new knowledge formulating the current understanding of visual impairment. While ICD-11 is intended to be a global standard, local classifications of visual impairment exist and vary by region. These are often referenced by research studies operating within them.

2.4.2. Classification of Visual Impairment in the UK

In the UK, the Certificate of Vision Impairment (CVI) is employed and intended to be completed by consultant ophthalmologists and hospital eye clinic staff for individuals with a visual impairment. It categorises an individual into one of the following.

- The person is sight impaired (partially sighted)
- The person is severely sight impaired (blind)

The CVI has undergone several revisions. In 2005, the CVI (2005) assessed whether sight varied markedly under different light levels. It also provided a comprehensive assessment of peripheral and central field loss in conjunction to a tabulated diagnosis of visual impairment (Great Britain. Department of Health and Social Care, 2005). A revised CVI (2018) was later published in 2018 to replace CVI (2005), maintaining the prior categorisation of visual impairment. It added self-reporting on the individuals' living circumstances, but excluded whether sight varied markedly under different light levels, and the comprehensive assessment of peripheral and central field loss (Great Britain. Department of Health and Social Care, 2018).

As such, CVI (2018) provides less information on the individual's visual function than CVI (2005). Instead, it adds emphasis on self-reported measures of functional vision to support patients' external care by local authorities. This is explained by the 2016-2017 consultation to revise CVI (2005) as an effort to 'simplify terminology, and ensure it captures the information to support people who may need help from local authorities' (Great Britain, Department of Health and Social Care, 2017).

It is also stated that the revision of the explanatory notes provided to those issuing the CVI have been updated to 'give clearer guidelines to who should be certified with sight impairment. The criteria for certification are based on visual acuity, extent of visual field loss together with the clinical judgement of the consultant ophthalmologist' (Great Britain. Department of Health and Social Care, 2017). Notably, the 2016-2017 consultation to revise CVI (2005) posed the following question:

> 'Is the judgement of the consultant ophthalmologist of the person's visual function, the best basis to certify people with sight impairment if they do not meet the visual acuity criteria?'

This is of particular relevance to prior findings on the use of visual acuity to determine visual impairment severity in ICD-11. 75% of the consultation group responded with 'yes', with 19% and 6% responding 'No' or not responding, respectively. This therefore supports the conclusion that visual acuity should not be used as the sole comprehensive representative of severity of visual impairment. Instead, the consultation suggests that it should be the professional judgement of the consultant ophthalmologist as to whether the person should be certified and, if so, whether as sight impaired (SI) or severely sight impaired (SSI) (Great Britain. Department of Health and Social Care, 2017). Moreover, the consulted sample included 69 responders from a large proportion of visually impaired organisations, local authorities, and healthcare trusts. This suggests a representative sample aided by subject-matter experts.

In summary, more ambiguity has been added in the later 2018 revision of the CVI. Three observations can therefore be made. Firstly, severity of visual impairment may not be

rigorously detailed by objective measures of visual function, and subjectivity from healthcare professionals may abrogate these. Secondly, the inclusion of measures of functional vision suggests that classifying visual impairment should be a holistic process investigating how a patient uses their sight. Hence, the importance of mixed reporting is confirmed. Thirdly, the CVI does not agree with classifications presented by ICD-11, showing that discrepancy can exist between global and local standards. Furthermore, ongoing revisions of the CVI continue to distinguish these two standards in their methods of classification.

2.4.3. Classification of Visual Impairment in International Research

The methods used in research to classify test groups is of significance. This is because a consistent classification should be employed to enable a fair comparison between results. As found previously, international standards present ambiguity. Consequently, this creates disparity in how visually impaired test samples are described. The table below indicates examples of research conducted internationally in the field of visual impairment, mobility, and evacuation. Note that these studies were selected as they did not target a specific cause of visual impairment. Rather, each study attempts to generalise visual impairment to observe how mobility changes in different operating scenarios. The following descriptions of test samples are summarised for brevity and readability (Table 2.3). Each is considered to convey no less relevant information than that presented in the study.

Reference	Title	Location	Test Sample
Samoshin & Istratov (2014)	The Characteristics of Blind and Visually Impaired People Evacuation in Case of Fire	Russia	201 visually impaired participants (68.2% over 40 years of age) classified according to Russian medical legislation where all people with disabilities are divided into 3 groups depending on their functional system of the body with the most severe problems relating to group I and the least to group III.
Sorensen & Dederich (2015)	Evacuation characteristics of visually impaired people – a qualitative and quantitative study	Denmark	40 visually impaired participants aged 10-69 years classified according to Danish classification (based on visual acuity ‘x’) as follows: A – Visually Impaired ($0.1<x\leq0.3$) B – Social blindness ($0.01<x\leq0.1$) C – Practical blindness ($0.001<x\leq0.01$) D – Total blindness ($x\leq0.001$)
Manduchi and Kurniawan (2011)	Mobility-related accidents experienced by people with visual impairment	United States	307 visually impaired survey participants aged 18 years and older asked to describe level of vision loss as either ‘blind’ (at most some light perception) or ‘legally blind’ (legally blind but not blind).
Long et al. (1990)	Mobility in Individuals with Moderate	United States	22 ‘low vision’ participants aged 19-58 years tested on visual acuity, visual field, and contrast sensitivity.

	Visual Impairments		
Swenor et al. (2013)	Does Visual Impairment Affect Mobility Over Time? The Salisbury Eye Evaluation Study	United States	2520 Salisbury Eye Evaluation Study participants aged 65 years and older followed over 2, 6, and 8 years after baseline. Visual impairment was defined as best-corrected visual acuity worse than 20/40, or visual field of approximately less than 20°.
Wright et al. (1999)	Emergency lighting and wayfinding provision systems for visually impaired people: Phase I of a study.	United Kingdom	30 participants aged 36-73 years classified only according to their cause of visual impairment including RP, Macular degeneration, Glaucoma, and Diabetic retinopathy.
Salive et al. (1994)	Association of Visual Impairment with Mobility and Physical Function	United States	Interview of 5143 older residents aged 65 years and older of three communities (Established Populations for the Epidemiologic Studies of the Elderly), classified according to visual acuity screening, self-reported activities of daily living and mobility, and objective physical performance measures of balance, walking, and rising from a chair.
Zhang et al. (2018)	Effect of obstacle density on the travel time of the visually impaired people	China	Eight sighted and 32 visually impaired participants classified as 'near blindness' in accordance with Chinese national standards aged 28-55 years. The range of vision loss (based on visual acuity) of the visually impaired people was <0.05 and described as being unable to walk without a walking stick or assistance from family members.
Leat & Lovie-Kitchin (2008)	Visual function, visual attention, and mobility performance in low vision	United States	35 visually impaired participants aged 20-80 years with low vision due to a variety of visual disorders classified according to UFV and clinical measures of contrast sensitivity, visual field, and visual acuity. Two series of models were considered; series 1 using the UFV scores as measured and series 2 using the UFV scores corrected for visual field loss (only counting errors in areas of intact visual field).
Brouwer et al. (2008)	Limitations in mobility: experiences of visually	The Netherlands	10 visually impaired older participants aged 63-95 at a Dutch centre for visual impairments with the following inclusion criteria:

	impaired older people		1. Had applied for mobility training at the centre 2. Had visual deficiencies 3. Were experiencing problems in mobility as a pedestrian 4. Had never before received mobility treatment 5. Had received treatment from someone other than the first researcher 6. Did not have any of the following problems: deafness or secondary psychiatric disabilities, or severe physical, diabetic or neurological disabilities 7. Spoke and understood Dutch 8. Were willing to participate in the study.

Table 2.3: Descriptions of test samples in a selection of studies investigating visually impaired mobility.

From this sample of 10 research papers, each presents a test sample characterised through a differing method of classification. In comparing Samoshin & Istratov (2014) and Sorensen & Dederich (2015), Samoshin and Istratov (2014) uses the Russian classification that functions on disability. In contrast, Sorensen & Dederich (2015) made use of the Danish classification system which is specific to visual impairment. Problematically, these systems do not account for similar variables and do not contain the same number of subdivisions, making it unreliable to compare across subdivisions.

Additionally, there is a disparity between the basis of classification within these systems. Specifically, visual acuity is employed in Sorensen & Dederich (2015), and broader bodily function is employed in Samoshin & Istratov (2014). The former is a measure of visual function and represents the fundamental capacity of the visual system. The latter could include other factors, including cognitive capacity, that sum to the individual's functional capacity. Experimental validity is therefore hindered.

Studies including Leat & Lovie-Kitchin (2008) and Swenor et al. (2013) present finer insight into their test sample through clinical measurements of visual function. Several functions are investigated including visual acuity and visual field. More objectivity in sample discretisation is obtained, as well as greater potential for reliable comparison. Leat & Lovie-Kitchin (2008) recognised Useful Field of View (UFV) (corrected and uncorrected for visual field) in conjunction with clinical measures of contrast sensitivity, visual acuity, and visual field. A greater understanding of how the individual's characteristics, such as age and visual attention through UFV measures, is obtained. This may not be possible in studies such as Zhang et al. (2018) where classification is lacking in precise value. For instance, 'visual acuity <0.05 and described as being unable to walk without a walking stick or assistance from family members.'

Leat & Lovie-Kitchin (2008) presents a limitation in that the participant's general health was not considered. This is recognised within the study as being a possible explanation for discrepancies in certain results. Namely, Leat & Lovie-Kitchin (2008) did not agree with findings from other studies showing strong correlation between walking speed and vision. This suggests that self-report and a natural history study of an individual can only serve to benefit

the research study. However, their inclusion is a time-consuming process. The specialist knowledge required to accurately determine visual function may also be cost and time prohibitive.

2.5. Prevalence of Visual Impairment Considering Age and Gender

The WHO (2021) states that there are at least 2.2 billion people globally with a near or distance visual impairment. 1 billion of these cases present a visual impairment that has yet to be addressed or could have been prevented. The most prevalent of which are 826 million with near vision impairment caused by unaddressed presbyopia, and 88.4 million with unaddressed refractive errors. This is followed by cataract (94 million), glaucoma (7.7 million), corneal opacities (4.2 million), diabetic retinopathy (3.9 million), and trachoma (2 million) (Vision Loss Expert Group of the Global Burden of Disease Study, 2021).

A significant proportion of global visual impairment results from addressable causes. More economically developed regions therefore present significantly fewer cases of visual impairment. Indeed, distance vision impairments in lower-income regions are four times more prevalent than in high-income regions. Such is exacerbated for near vision impairments, with approximately seven times more prevalence in lower-income regions in comparison to high-income regions (Vision Loss Expert Group of the Global Burden of Disease Study, 2021).

Consequently, while addressable visual impairment prevails globally, visual impairments that are difficult to treat remain significant. This is especially so in higher-income regions where they may become the most prevalent cause of impairment. For instance, Li et al. (2020) explains how AMD continues to be the main cause of visual impairment in Europe given its aging population. Liew et al. (2014) finds that HRDs have become the most prevalent cause of blindness in the working age group (16 to 64 years of age) in the UK. However, while the medical causes of visual impairment can be listed and totalled, the corresponding severity of impairment can also be collected and quantified. This provides an understanding of the actual impact on sight from these visual impairments.

According to a systematic global estimate of visual impairment in 2010 by Pascolini and Mariotti (2010), there are 285 million visually impaired people in the world. This figure comprises 39 million people that are blind and 246 million that have low vision. Another systematic review of the global prevalence of visual impairment was conducted by Bourne et al. (2015) where it was estimated that 36.0 million people are blind, 216.6 million have a moderate to severe visual impairment, and 188.5 million that have a mild visual impairment.

Bourne et al. (2015) found that visual impairment was somewhat more prevalent in females than in males, reporting that females made up 56% of those that are blind, 55% of those that have a moderate to severe visual impairment, and 54% of those that have a mild visual impairment. Rius Ulldemolins et al. (2019) explains that such could be the result of gender inequalities, finding a higher prevalence of visual impairments and related cataracts in females. This coincides with inequality in access to healthcare.

In men, undiagnosed eye disease and related glaucoma prevailed, possibly explained by gender-related social perception and a consequently reduced reliance on healthcare. This was found to be consistent regardless of age or level of education. Note that this study is limited as findings were based on data collected from a Spanish survey conducted in 2008, thus impairing

the certainty of these findings for the global population. Other international studies do, however, support these conclusions; it is found that gender inequality and a prevalence of treatable visual impairments (cataracts) exist in regions such as El Salvador (Rius et al., 2019), Egypt (Mousa et al., 2014), and Nigeria (Rabiu et al., 2012).

The WHO (2021) states that visual impairment becomes more prevalent with age, explaining that the majority of people with visual impairments are over 50 years old. From observing a cluster-stratified random sample of 5147 residents aged 40 years and older, Weih et al. (2000) explains that predominant causes of visual impairment vary by age. These increase in severity with increasing age (Figure 2.6). As suggested by Dandona and Dandona (2006), Weih et al. (2000) considered uncorrected refractive error and several levels of severity in their classification using both visual acuity and visual field measurements:

1. Mild: Less than 20/40 to 20/60 and/or homonymous hemianopia
2. Moderate: Less than 20/60 to 20/200 or better and/or less than 20° to 10° radius field
3. Severe: Less than 20/200 to 10/200 and/or less than 10° to 5° radius field
4. Profound: Less than 10/200 and/or less than 5° radius field (profound)

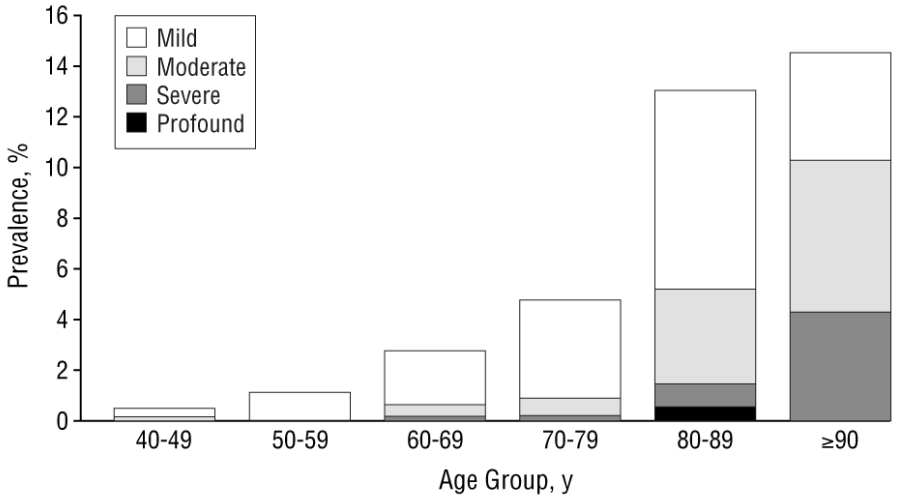


Figure 2.6: Severity of visual impairment by age in over 40s (Weih et al., 2000).

Uncorrected refractive error was the most prevalent form of bilateral visual impairment within the sample observed by Weih et al. (2000), rising from 0.5% in 40-49-year-olds to 13% in people aged 80 years and older. This was followed by diabetic retinopathy, starting from 0.7% in 50-59-year-olds rising to 0.8% in people aged 80 years and older. Glaucoma then prevailed at 0.7% in 60-69-year-olds rising to 4% in people aged 90 years and older. In older age groups, cataract was only prevalent in people aged 70 years and older, starting from 0.6% and rising to 11% in people aged 90 years and older. As was AMD, starting from 0.8% and rising to 16% in people aged 90 years and older (Weih et al., 2000).

Visual impairment is also prevalent in children and young adults although, as explained by Gilbert et al. (1999), prevalence is much lower in comparison to older adults. This is following a review of available data (global registers of the blind, birth cohort studies, community-based surveillance systems, and population-based prevalence surveys). However, this may be a result of small sample sizes and the difficulty of measuring visual function in younger children. Gilbert et al. (1999) explains that a young or disabled child may not possess the concentration,

educational development, and verbal skills required for reliably measuring visual acuity using conventional methods (such as the Snellen chart).

Coverage is also limited in that children may attend schools, be with relatives, or be hidden from surveys and registers (resulting from stigmas associated with disability). It is therefore likely that their visual impairment may not be recorded until later life (Gilbert et al., 1999). Additionally, impacts on visual function from progressive diseases such as RP may only become noticed and measured in later life. This was found by Stewart-Brown & Haslum (1988) following 15,000 English children born in 1970. 85% had their acuity measured at 10 years of age where 5 children were found to have an acuity below 6/60 (severe visual impairment/blindness).

The prevalence of visual impairment in children may be ten-fold in the world's poorest countries relative to the wealthiest for similar reasons described by Mousa et al. (2014) and Rabiu et al. (2012) in Egypt and Nigeria. These include a lack of sufficient diagnosis and treatment. Gilbert et al. (1999) states that accurately determining the prevalence of different causes of visual impairment in children is difficult. Qualitative conclusions on how visual impairment prevails in children are therefore drawn from Liew et al. (2014) (reviewing 1756 CVIs from the Certifications Office from persons aged between 16 and 64), Kalikivayi et al. (1997) (analysing 4029 school children aged between 3 and 18 in Southern India), Rahi & Cable (2003) (observing 439 newly diagnosed children in the UK), and Gilbert et al. (1999),

Excluding uncorrected refractive error and undiagnosed visual impairments, HRDs remain the most prevalent registered causes of visual impairment in adults and children (Liew et al., 2014; Gilbert et al., 1999). Gilbert et al. (1999) then finds amblyopia, corneal, optic nerve, infections, trauma, cataract, and vitamin A deficiencies to be prevalent causes of visual impairment in registers from Asia and Africa. While none within the sample of schoolchildren observed by Kalikivayi et al. (1997) following refractive correction could be classified as blind/profoundly visually impaired, hyperopia (22.6%), myopia (8.6%), and astigmatism (10.3%) were observed. 1.4% presented a corrected visual acuity of less than 6/9 in the worse eye resulting from amblyopia (1.1%), corneal diseases (0.1%), cataract (0.05%) and other causes (0.1%). 0.7% had strabismus.

Rahi & Cable (2003) explains that 77% of the observed sample of newly diagnosed children had non-ophthalmic disorders, with a 10% mortality rate within one year of diagnosis of blindness. Indeed, non-ophthalmic conditions including Cerebral Palsy (Black, 1982) and other cortical/cerebral visual impairments (caused by perinatal hypoxia, brain injury, seizure disorder and other associated neurological abnormalities) can prevail in children (Martin et al., 2016). These lead to more severe physical and sensory impairments than age-related causes of visual impairment described by Weih et al. (2000).

2.6. Conclusions on Modelling Human Behaviour and Classifying Visual Impairment

Human behaviour modelling is a mesoscopic process. To be effective, it requires an understanding of the individual and their behaviours in a crowd. Several modelling principles exist, although mesoscopic operation is difficult to achieve. This is particularly true for a visually impaired individual where their ability is fundamentally changed. A process is therefore devised to deliver a mesoscopic understanding of visually impaired mobility. This

begins with mobility capacity (comprising the human factors) and transitions to mobility performance. Finally, a framework of requirements can be derived.

This chapter addressed the fundamental human factor affecting visual impaired individuals. This is their reduced biological function, termed visual function. Visual acuity, visual field, contrast sensitivity, and colour vision are explored in the context of the visual system and its diseases. Visual impairments are found to affect each visual function differently, and these are listed in detail. Moreover, the predictability and measurement of each function is confirmed.

It is found that measurements of function vary according to external factors. They should therefore only be used to predict mobility if they are conducted under the same conditions as any mobility testing. It is also argued that clinical measures of function are inappropriate for conclusive real-world predictions of functional vision (Genensky et al., 1979). Moreover, varied international classifications of visual impairment hinder the comparability of regional studies that use them.

Age, gender, and region should be considered when assessing a visually impaired test group as each may influence the cause and treatment of visual impairment. In children, this could be a result of neurological abnormalities that could profoundly physically and cognitively impair the child. Contrastingly, age-related diseases including AMD can occur at old age where physical and cognitive capacity may deteriorate. In developing countries, treatable causes of visual impairment prevail. However, correct diagnosis and treatment could lead to substantially improved mobility without further intervention. Such may affect females more than males as a result of gender inequalities in these regions.

Finally, correct classification of visual impairment with an understanding of these aforementioned factors will allow for the derivation of appropriate user requirements. For instance, in children with neurological impairments, visual impairment may not be the limiting factor on mobility. Solutions to improve mobility will therefore need to consider this accordingly. Likewise, in developing countries, correction of uncorrected refractive error would be a more appropriate and cost-effective method of meeting user requirements.

3. Mobility Capacity of Visually Impaired People in Individual and Group Behaviour

As described in Chapter 2, the investigation of mobility capacity forms the first phase of holistically understanding visually impaired mobility. This comprises the fundamental biological and human factors governing the individual, operating on their own or in a crowd. This chapter identifies the causal factors of mobility capacity while considering the impacts of visual impairment on visual function, found in Chapter 2. Section 3.1 introduces the chapter and the important of considering mobility capacity. Section 3.2 proceeds to investigate this in the context of individual mobility, while section 3.3 does so in the context of group behaviour. In both, physiological and psychological factors are discretised and explored. Section 3.4 summarises these findings. Throughout this process, discrepancies are found in the literature's application of mobility outcome measures, and these are discussed in section 3.5. To conclude the chapter, section 3.6 summarises findings and proposes the next phase of this research.

3.1. Importance of Including Individual and Group Behaviours in Visually Impaired Mobility

The biological processes responsible for visual impairment and their classification are now understood. A critical review of the physiological and psychological processes governing the mobility capacity of a visually impaired individual can now proceed. As realistic human behaviour modelling requires a mesoscopic approach, a further distinction is made between the behaviour of the individual and the crowd (Bellomo et al., 2016a). This is especially as both individual and crowd behaviours are then inherent to a range of different operational scenarios. These range from individual mobility performance when evacuating a dwelling to wayfinding in congested urban spaces.

In addition to differentiating physiological, psychological, individual, and crowd factors, these must then be contextualised to the environments in which they occur. These are 'scenarios'. For instance, an emergency evacuation can occur in a private dwelling or public space, each typically representing vastly different mobility performance (Proulx & Fahy, 2001). Scenarios are effective in testing and validating the objectives of environments, services, or products. Such has been used in several applications, including software development (Van Lamsweerde & Willemet, 1998), population health (Pelissari et al., 2018), and atomic physics (Medina et al., 2019). Scenarios can be generically separated into those occurring on a typical basis, such as through activities of daily living, and those that occur in atypical circumstances, such as an emergency evacuation.

To determine the causal factors of visually impaired mobility capacity, generic factors affecting mobility are considered. These are factors inherent to the individual, and not the environment or scenario in which they operate. Further analysis on how these are augmented in realistic environments is conducted in Chapter 6 (mobility performance). The following figure (Figure 3.1) displays these factors as derived from the reviewed literature. These factors can relate to both typical and atypical scenarios, and each factor is observed in the context of both.

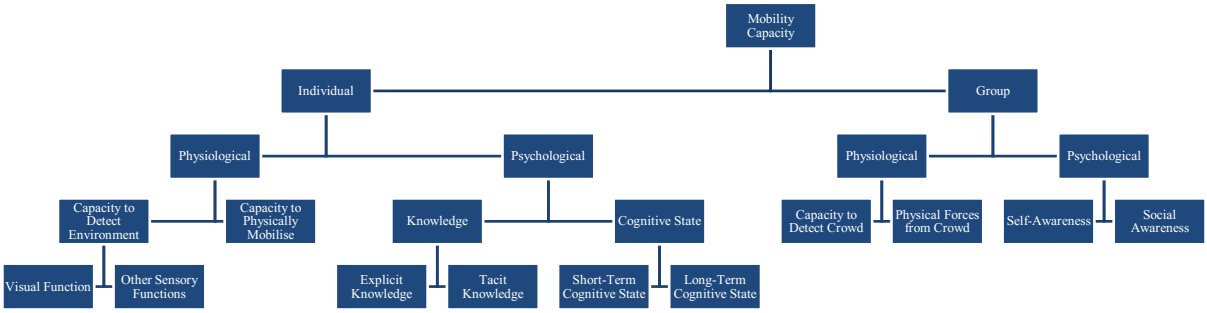


Figure 3.1: Factors that influence the mobility capacity of a VIP.

3.2. Observing the Mobility Capacity of Visually Impaired People from Individual Behaviour

3.2.1. Physiological Factors in Individual Behaviour

It is well-understood that sight is the primary source of information used by pedestrians to control their motion (Batty, 1997; Gibson, 1958; Schrater, 2000). Therefore, it can be inferred that an explicit impact to a visually impaired person's mobility arises from the physical manifestation of visual impairment on the eye. Previous ophthalmic research has either investigating the impact of specific causes of visual impairment on mobility, or how certain parameters of sight correlate with mobility. For clarity and ease of comparison, research investigating specific visual impairments is included with descriptors of how such visual impairments typically affect visual function.

3.2.1.1. Capacity to Detect Environment

Visual acuity, visual field, contrast sensitivity, and colour vision are broad measures of visual function that have been explored in mobility research. However, it is difficult to independently ascertain how each measure individually impacts mobility given their concurrent and relativistic nature. Firstly, the clinical significance and widespread understanding of visual acuity catalyses its prevalence in visually impaired mobility research. Katemake et al. (2019) tested 60 participants with simulated visual impairment divided equally into groups with tunnel vision, blurred vision, and central scotoma (in order of increasing severity on central visual acuity). The environmental augmentations adapted by Katemake et al. (2019) are discussed in Chapter 6.

Those with blurred and tunnel vision showed similar performance, but it was found that participants with blurred vision experienced discomfort from glare, causing an increase in obstacle collisions. This suggests that environmental features including illumination can impact visual function. Central scotoma was found to cause the widest range of obstacle collisions per participant, with participants using remaining vision surrounding the central

blind spot to orientate. Such reiterates that visual acuity is closely linked with visual field and contrast sensitivity. This is as, while central visual acuity may be profoundly reduced through central scotoma, useable vision in the wider peripheral field may still be critical to mobility capacity.

Katemake et al. (2019) presents an important limitation that should be addressed in future work. This is that none of the participants were visually impaired, and all had normal visual acuity and no colour blindness. Instead, visual impairment was induced through wearing binocular glasses (Lustiner, France) to simulate the three categories of visual impairments tested. This negates the adapted spatio-cognitive ability and knowledge possessed by a biologically visually impaired participant. The reliability of these findings is therefore reduced (Passini et al., 1990). However, the findings are still relevant given a relatively large number of participants (60) with a broad range of ages (20 to 53 years old) and balanced genders (35 males and 25 females).

Indeed, Katemake et al. (2019) observed the undue influence of induced visual impairment on the realistic applicability of the experiment. It is stated that the participants' goal was to 'avoid obstacles easily but also to accelerate as much as possible the end of the experiment in order to avoid the annoyance caused by the simulated visual impairment.' The division of a normally sighted population through induced impairment is therefore beneficial for controlling the participant sample. However, it cannot be applied to the holistic quantification of a visually impaired person's realistic mobility.

Marron and Bailey (1982) conducted experimentation to ascertain how residual vision in visual acuity, visual field, and contrast sensitivity affect orientation and mobility. The testing sample comprised 19 patients from the patient population of the Western Blind Rehabilitation Centre, Veterans Administration Hospital in Palo Alto. Orientation and mobility were tested via an indoor and outdoor mobility course, counting the number of orientation errors (E) as the mobility outcome measure. It was found that visual field and peak contrast sensitivity were the primary determinants of orientation and mobility. Log VF and log peak CS accounted for 30% and 33% of the variation in mobility, respectively. Together, they accounted for 53% of this variation. The following novel mathematical relationship was therefore proposed by Marron and Bailey (1982):

$$OM_j = \beta_1 + \beta_2 \mathrm{VF_j} + \beta_3 CS_j$$

Where:

- OM_j is the orientation and mobility performance, log100/(1+E), for the jth individual
- VF_j is the individual's measured remaining visual field (log%VF)
- CF_j is the individual's measured peak contrast sensitivity (log peak CS)
- β_1, β_2, and β_3 are non-standardised weighting factors

And in considering the data collected by Marron and Bailey (1982) for the sample observed, the following predictive model was found:

$$OM_j = 0.22\mathrm{VF_j} + 0.70CS_j - 0.19$$

Remarkably, visual acuity was not found to be a major descriptor of mobility. Limitations do arise in the study in that temporal contrast sensitivity was excluded, and only spatial contrast sensitivity was measured using grating patterns. Visual fields were determined at 1 m by using a 2.4 x 2.4 m tangent screen. This allowed plotting of the visual field out to 40 degrees from

the fixation point, thus not rigorously covering each quadrant of visual field as is possible with dedicated measuring equipment. Moreover, Marron and Bailey (1982) agree that measuring orientation and mobility is not a standard process, and so an indoor and outdoor course were designed. The courses differed in layout, and illumination could not be controlled in the outdoor course, a factor known to affect mobility (Kuyk et al., 1998; Katemake et al., 2019; Black et al., 1997).

Some psychological factors were controlled as patients that had only spent limited time at the facility were selected. Furthermore, only patients that were ambulatory without mobility aids and had light perception (at least) were included. Therefore, while the mathematical relationship derived by Marron and Bailey (1982) is notable and estimates how several visual functions concurrently affect mobility, it is not conclusive. Further research into other visual functions is necessary with a broader test group, including those that have no residual vision as was negated by Marron and Bailey (1982).

As was noted by Marron and Bailey (1982) in the indoor and outdoor mobility course, the environment in which the individual operates can determine visual performance within that environment. Kuyk et al. (1998) exemplifies this through correlating measures of visual and perceptual function in the performance of realistic mobility tasks, and how these vary when light level changes from photopic to mesopic. Note that further analysis of environmental illumination to augment mobility is conducted in Chapter 6, and this research is referenced to contextualise visual function variability according to environment.

Kuyk et al. (1998) measured visual acuity, peak letter contrast sensitivity and spatio-temporal contrast sensitivity, visual field extent, glare disability, colour confusion, motion sensitivity, scanning ability, and figure-ground discrimination to determine their ability to predict mobility. 87 and 66 older visually impaired adults were observed in an indoor hallway and outdoor residential route, respectively. All participants were also tested on an indoor laboratory course within the testing period. Indeed, Kuyk et al. (1998) presents an extremely comprehensive suite of medical testing with a relatively large sample size. Although, limitations are present in that predominantly older male veterans with a very broad range of visual impairments were observed, with different testing groups per environment.

Kuyk et al. (1998) concluded that 30% to 42% of the variance in overall performance, regardless of environment, was correlated to four measures of function. The two most predominant of which were measures of visual field (visual field extent and scanning ability), followed by colour confusion, spatial contrast sensitivity, and spatial resolution. The inclusion of visual field and spatial contrast sensitivity agrees with findings from Marron and Bailey (1982). Moreover, the time to complete routes and the number of mobility incidents increased significantly under mesopic conditions. This confirms that environmental characteristics can universally detriment all function and mobility, especially in the context of mesopic conditions.

In addition to findings from Marron and Bailey (1982) and Kuyk et al. (1998), research suggests that the nature of visual field loss can determine mobility capacity. This is considering aspects of peripheral vision, central vision, and their dynamic variation. A reduction in peripheral vision reduces a subject's ability to capture and process an environment and its features that are not directly in line of sight. Indeed, those with reductions in peripheral vision may present good acuity until the later stages of disease, such as those suffering from RP and other retinal dystrophies (Dickinson, 1998; Vargas-Martín & Peli, 2006). It is therefore

presumed that those with peripheral vision loss may increase the rate and breadth in which they scan their environment, using such methods as greater and more frequent head and eye movements. This is to increase their real-world field of vision, termed the dynamic visual field, to compensate for the losses in their static visual field (Dickinson, 1998).

Turano et al. (2001) and Vargas-Martín & Peli (2006) conducted research in the ability of those with reduced peripheral vision to scan their environments while walking. These studies differed in that Turano et al. (2001) did not differentiate between head and eye movement, finding that the mean angular area scanned by the visually impaired test group was three times that of the normally sighted control group. Vargas-Martin & Peli (2006) found that the visually impaired subjects tested did not increase horizontal eye movements to compensate for field loss. Additionally, the visually impaired subjects actually presented a narrower horizontal eye dispersion in comparison to the normally sighted control group. It was thought that the reduction in visual stimulus in the visual field may have caused this.

It is therefore noted that those with visual field loss may not effectively scan their environments, and that is also environment-dependant. Differences when operating in an indoor or outdoor space are particularly significant (Kuyk et al, 1998; Vargas-Martin & Peli, 2006). This leads Vargas-Martin & Peli (2006) to suggest that immersive head-mounted mobility aids should consider a Field of Views (FOV) as wide as 40°, with narrower FOVs in open designs.

The study conducted by Vargas-Martin & Peli (2006) was limited in that the test group was relatively narrow, featuring five patients with severe peripheral vision loss from RP and a control group of three normally sighted participants. Similarly, Turano et al. (2001) only observed visual impairment arising from RP. While the environments tested were realistic, utilising both indoor and outdoor spaces with dynamic obstacles, the routes followed by each participant were not identical. These featured uncontrolled elements such as obstacle positioning, construction work, and sun position. While Turano et al. (2001) observed subjects walking for one minute, Vargas-Martin & Peli (2006) observed each subject for at least 30 minutes.

A process of environmental acquisition through a reduced visual field can thus be proposed as follows (Figure 3.2):

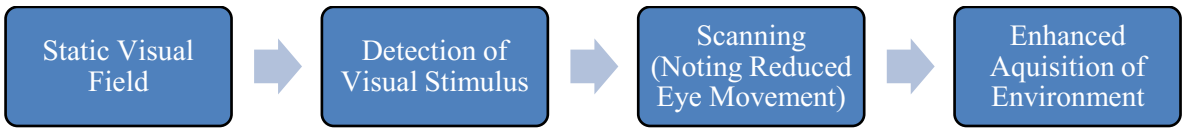


Figure 3.2: Environmental acquisition through reduced peripheral vision.

Utilising controlled environments with spatially diverse visual stimuli is therefore critical to obtaining a realistic understanding of visual field loss. Moreover, subjects with a range of visual impairments should be considered given that specific visual impairments, such as RP, often have a unique manifestation to the visual field. Indeed, research with broader visually impaired test groups has been conducted to explore how the visual field affects mobility.

The Salisbury Eye Evaluation is a particularly notable study where, in its third round, 1504 older adults between the ages of 72 and 92 were enrolled to determine the association between visual field loss and orientation and mobility (Turano et al., 2004). This research did conclude

that visual field loss is associated with reduced mobility, observing that reductions in the visual field led to reduced walking speeds and greater collisions with obstacles. Orientation errors were not found to be associated with peripheral vision loss. It is also found that the large testing sample in this study presented different forms of field loss, and three visual field regions were therefore tested. These were the central, upper, and lower peripheral vision regions. Manifestations of the central and lower peripheral regions had the greatest impacts on walking speed, with losses in central vision also increasing the likelihood of bumps and collisions (Turano et al., 2004).

While the study only investigates visual field loss in older adults, adjustments were made for age, gender, and health characteristics that could impact mobility. Additionally, all participants were tested using the same circuitous, 32.8 m long obstacle course. Such highlights the importance of using fair testing and controlled environments in mobility research. The findings by Turano et al. (2004) do not, however, align with findings from Subhi et al. (2017) where it was concluded that peripheral vision is a better predictor of mobility function. It should be noted that Subhi et al. (2017) employed a very different testing methodology than that of Turano et al. (2004); Subhi et al. (2017) used self-reporting methods and a smaller sample size in comparison to the practical mobility testing used by Turano et al. (2004).

Such differences in methodology lead to difficulty in identifying specific factors that explain this disparity. Furthermore, a study by Haymes et al. (1996) found the concentric visual field as also being a key indicator of mobility in conjunction with contrast sensitivity in patients with RP. RP impacts sight differently to the diseases observed in studies including Turano et al. (2004) and Subhi et al. (2017). This indicates the complex influence of other metrics of sight pertaining to specific diseases on mobility. It is therefore suggested that mobility testing should be specific to similar causes of visual impairment, or should also consider other metrics of sight in making conclusions.

Black et al. (1997) supports this conclusion, conducting a study of 10 participants with RP and nine age-matched control subjects to investigate mobility under changing environmental illumination. Visual field, contrast sensitivity, and average visual field extent were clinically measured for each participant. Visually impaired participants presented reduced walking speed and increased error when compared to the normally sighted group. This was especially under low illumination. Multiple regression analysis found that visual field was the primary predictor of mobility, added with contrast sensitivity and visual acuity to account for up to 75% of the variation in mobility.

In summary, mobility testing considering visual field loss should also consider the region of the impacted field as this may determine mobility capacity. For instance, the impacts of ground-level obstacles may be more pronounced on the mobility of those with poorer central and lower peripheral vision. Additionally, the importance of residual vision as an indicator of mobility is affirmed, where mobility is expected to decrease with residual vision loss (Turano et al., 2004; Haymes et al., 1996).

Leat and Lovie-Kitchin (2006) presents a study that introduces discrepancy between visual field measures and resulting mobility. This involved testing 35 participants with several visual impairments causing low vision, using diverse functional measures including visual detection distance and visual identification distance, as well as simple measures of walking speed and orientation errors. The test group was diverse in its coverage, including an age range of 20 to

80 years old with a mixture of congenital and age-related diagnosis including albinism, cataract, glaucoma, Stargardt disease, Retinopathy of prematurity, AMD, and more.

It was found that measured Humphrey visual field mean deviation, visual acuity, and contrast sensitivity grouped with mobility errors, visual detection distance, and visual identification distance. This was not the case for walking speed and preferred walking speed. Humphrey pattern standard deviation did not group with any other measure and neither did percentage preferred walking speed. This further suggests that measures of walking speed are not directly related to visual function.

Leat and Lovie-Kitchin (2006) shows good repeatability in that visual field and contrast sensitivity (and occasionally low contrast visual acuity) were the best clinical visual predictors of mobility. This concurs with the findings of priorly-observed studies. Furthermore, the testing environment used by Leat and Lovie-Kitchin (2006) is more rigorously crafted than any preceding study. It sets the foundation for environmental design considerations in the testing of visually impaired mobility and is further detailed in Section 3.5.

Finally, it is observed that the included studies either investigated groups with different visual impairment diseases (defining correlations of function and mobility for widely variable visual functions), or a controlled group with a single cause of visual impairment. Each approach presents limitations, as priorly discussed in each study. To address this, these studies are reobserved from the perspective of the visual impairment disease, rather than parameters of visual function.

For instance, Turano et al. (1998) and Haymes et al. (1996) both highlight a strong relationship between contrast sensitivity, visual field, and mobility when investigating patients with RP. Here, however, contrast sensitivity, peripheral vision, and low-light vision are significantly variable and progressively hindered as the disease progresses with age. Likewise, Geruschat et al. (1998) found that 70% of the variance in tested RP subjects' walking speed was accounted for by log CS and visual field extent. It was also added that 80% of the RP subjects experienced mobility difficulty from responses to a mobility questionnaire.

This demonstrates that self-reported behaviours were statistically related to walking speed in addition to visual function. Moreover, the mobility challenge associated with this particular visual impairment is one that dynamically and progressively changes in the long-term with decreasing function and increasing age. This is rather than just short-term variation in the environment, as suggested by Kuyk et al. (1998).

The inclusion of a normally sighted control group with a visually impaired sample can produce a better understanding of how visual impairment relatively impacts capacity. This was demonstrated by Turano et al. (1999) in investigating the mobility of 47 glaucoma patients and comparing this to a control group of 47 participants without visual impairment of similar age. As with RP, glaucoma causes progressive visual impairment, and the aim of this research was to therefore establish how glaucoma affects mobility. This includes determining if a relationship between mobility and the stage of disease exists, supported by measurements of visual function.

Mobility was assessed by measuring the time, computing walking speed, and counting the number of mobility incidents to complete an established travel path. Two methods of visual field assessment were utilised, Humphrey 24-2 (monocular) and Esterman scale (binocular). In

the tested participants with glaucoma, the Humphrey 24-2 test yielded results that better correlated with walking speed than that scored by the Esterman scale, or than visual acuity or contrast sensitivity. It can therefore be concluded that walking speed decreases with severity of the disease and is best estimated by threshold perimetry.

Through provision of the control group, it was found that participants with glaucoma have a walking speed that was, on average, 10% below that of the control group. Moreover, twice the number of participants with glaucoma experienced bumps, stumbles, or orientation problems relative to the control group. However, this difference was not statistically significant. Additionally, reported falling (38% for the glaucoma group and 30% for the control) and fear of falling (28% for the glaucoma group and 23% for the control) was not statistically significantly different between the two groups. This conclusion confirms that mobility capacity may not be exhaustively determined by one outcome measure, and that a mixture of outcome measures should be employed per study.

Brown et al. (1986) and Goodrich and Ludt (2003) both investigated the mobility of participants with age-related maculopathy (ARM). Their methods are compared in the following table (Table 3.1). Brown et al. (1986) found that visual function measures, including velocity perception, could predict the mobility of patients with ARM. Specifically, the ratio of acuities in photopic and scotopic conditions correlated to functional mobility. Their use was therefore recommended as a new clinical approach to the prediction of mobility in patients with ARM. This agrees with all previous studies that visual function should be measured and compared at photopic and scotopic luminance levels, providing a useful indicator of functional residual vision. Moreover, Brown et al. (1986) suggests that simple variables including the time to complete a course and walking speed are those which correlate best to vision.

Attribute	Brown et al. (1986)	Goodrich and Ludt (2003)
Test subjects	18 subjects (8 male, 10 female), 10 with ARM and 8 age-matched normally-sighted participants acting as a control	60 subjects with ARM (56 male, 4 female) with an age range of 49-93 years
Mobility course	Indoor mobility course at photopic and scotopic adaptation levels	Outdoor travel path at daylight (photopic) level
Measured visual function	Visual acuity (Bailey-Lovie high-contrast chart, Amsler grid, Farnsworth Panel D-15 test) and visual field (macular and complete) and velocity perception	Visual acuity (LogMAR) and contrast sensitivity (Pelli-Robson)
Mobility outcome measures	Automated and video recorded data collection: Average speed; average deviation from average speed; root mean square deviation from average speed; average deviation from an ideal path; root	Manual data collection: Distance Visual Recognition Assessment (DVRA) with initial, potential, and final assessment prior to and following instructions from O&M instructor on

	mean square deviation from an ideal path; average acceleration; number, position, and duration of stops; latency to begin walking after given cue to start; total time to complete course; total distance travelled.	detecting hazards and environmental cues.

Table 3.1: Comparing the study methods of Brown et al. (1986) and Goodrich and Ludt (2003).

Goodrich and Ludt (2003) find that the ARM patients were unable to visually detect some hazards at a safe distance, but that improvements in ability can be predicted from the assessment structure utilised (initial, potential, and final). Indeed, Goodrich and Ludt (2003) suggests that subjects can improve their ability to visually detect obstacles if provided appropriate training and filters. This corroborates the functional potential of tacitly developed cognitive abilities in visually impaired individuals, acting in conjunction with quantitively measured visual function to influence mobility.

In comparing Brown et al. (1986) and Goodrich and Ludt (2003), it is apparent that the implemented measures of visual function and functional mobility are very different. Such is further explored in Section 3.5. In summary, Goodrich and Ludt (2003) employ a unique approach relative to Brown et al. (1986) and other studies investigating visual function. This is that a phased development of the participant's functional performance was conducted, rather than a single assessment of mobility. Indeed, Brown et al. (1986) demonstrate a more qualitative and automated data collection methodology in comparison to Goodrich and Ludt (2003). While this is more useful in determining a snapshot of visual function and functional performance, Goodrich and Ludt (2003) provide more context as to how visual function and cognitive processes interact. This includes how they build upon each other in the determination of realistic functional performance. These studies are therefore complimentary, and each is valid in presenting new findings on the mobility capacity of patients with ARM.

The capacity to detect an environment extends beyond visual function in that this is a multisensory process including auditory, tactile, and olfactory function (Jenkins et al., 2015). While impairments in these additional functions are outside of the scope of this study, it remains important to reaffirm their ability to affect mobility. To this effect, Ashmead and Wall (1999) found that sound reflectance allowed for the detection of walls, and Kellogg (1962) and Rice (1967) concurred in that this also benefited visually impaired people in detecting the size and compositions of specific objects. Attenuation of sound through sound 'shadows' cast by objects is also useful in the context of wayfinding (Gardiner & Perkins (2005); similarly to visual function, adaptation to auditory function through training can contribute to cognitive maps and improved mobility regardless of operating environment (Wiener & Sifferman, 1997; Easton & Bentzen, 1999).

Tactile feedback similarly contributes to the user's detection of their environment, particularly in improving safety through tactile paving, drop-off, and object detection (Jenkins et al., 2015; Wiener & Sifferman, 1997; Kim and Emerson, 2014). Research into olfactory detection and impacts on mobility capacity has primarily been hypothetical; Cuevas et al. (2010) demonstrated that individuals with long-standing visual impairments presented better odour

discrimination than their normally sighted counterparts. Gardiner and Perkins (2005) did not find this to be useful in cognitive mapping, but rather to aid in the understanding and processing of other sensory stimuli.

In visually impaired individuals, dependence on the remaining unimpaired sensory function is elevated. Such is why rehabilitation programmes, infrastructure operators, and mobility aid developers prioritise their use in improving visually impaired mobility performance, as is further detailed in Chapter 6 (Gardiner and Perkins, 2005; Jenkins et al., 2015; Lewis et al., 2015; OrCam, 2022; Meijer, 1997; Kajimoto et al., 2006; Kajimoto et al., 2014). Impairments in these functions can therefore hinder the information that the individual can use through similar mechanisms as impaired visual function. Vos et al. (2017) proves this to be particularly prevalent for age-related (and other) hearing loss, the third leading cause of disability (according to years lived with disability). Here, visual impairment, cognitive impairment, frailty, and a reduced ability to physically interact with the environment are likely to coincide with older age (Weih et al., 2000; Gale et al., 2015; Maharani et al., 2018).

3.2.1.2. Capacity to Physically Mobilise

Visual function is shown to be a determining factor in mobility. However, several other sensory and physical impairments can affect an individual's ability to mobilise, both in capacity and performance. These can include physical mobility impairments requiring wheelchair use, crutches, and step-free access, or hearing impairments that reduce sensing of auditory reference points (Gale et al., 2015; Vos et al., 2017). Table 3.2 from Transport for London (TfL) (2015a) exemplifies this through investigating the diverse communities that use London's transport network. A sample of 15,700 transport users was randomly selected and surveyed, finding that 1,821 users had a disability. This amounted to approximately 12% of the total population. Only 6% of the disabled population appears to have a visual impairment, with the majority of other travellers experiencing other disabilities that affect travel.

Demographic	% of all Londoners	% of disabled Londoners
Disability affects travel	10	90
Ever used a wheelchair	2	16
Mobility impairment	6	58
Serious long-term illness	2	21
Mental health condition	1	11
Visual Impairment	1	6
Hearing Impairment	1	5
Learning disability	1	7
Other	1	14

Table 3.2: Disabilities experienced by transport users in London (TfL, 2015a).

The preceding research on the impact of visual function on mobility excluded participants with moderate to severe impairments beyond visual impairment. However, an individual can possess several disabilities. Given that visual impairment is likelier to occur with age, it is possible for a visually impaired individual to experience an unrelated mobility impairment that limits their capacity beyond the impacts of visual function (Freedman et al., 2002). For instance, these could be frail older adults that can only maintain a reduced walking speed (Himann et al., 1988)

or wheelchair users that are unable to access entire environments given physical constraints (Boyce et al., 1999b; Welage & Liu, 2011).

Boyce et al. (1999b) observed how a range of mobility impairments beyond visual impairment can affect walking speeds. A horizontal level plane with a length of 50 m tong was used, as well as upward and downward ramps inclined between 3° and 4° with a continuous handrail. This is considered sufficient to demonstrate differences in walking speed. Table 3.3, as follows, has been extracted from Boyce et al. (1999b) to display the variability in walking speed that is possible between such mobility impairments.

Experiment with Disabled Subjects[6]					
On horizontal (m/s)	*Min*	*1st Q*	*3rd Q*	*Max*	*Mean*
All disabled subjects	0.10	0.71	1.28	1.77	1.00
With locomotion disability	0.10	0.57	1.02	1.68	0.80
No aid	0.24	0.70	1.02	1.68	0.95
Crutches	0.63	0.67	1.24	1.35	0.94
Cane	0.26	0.49	1.08	1.60	0.81
Walker/Rollator	0.10	0.34	0.83	1.02	0.57
Without locomotion disability	0.82	1.05	1.34	1.77	1.25
Unassisted wheelchair	0.85	--	--	0.93	0.89
Assisted ambulant	0.21	0.58	0.92	1.40	0.78
Assisted wheelchair	0.84	1.02	1.59	1.98	1.30
On upward incline					
All disabled	0.21	0.42	0.74	1.32	0.62
With locomotion disability	0.21	0.42	0.72	1.08	0.59
No aid	0.30	0.48	0.87	1.08	0.68
Crutches	0.35	--	--	0.53	0.46
Cane	0.21	0.38	0.70	1.05	0.52
Walker/Rollator	0.30	--	--	0.42	0.35
Without locomotion disability	0.70	--	--	1.32	1.01
Unassisted wheelchair	0.70	--	--	--	--
Assisted ambulant	0.23	0.42	0.70	0.72	0.53
Assisted wheelchair	0.53	0.70	1.05	1.05	0.89
On downward incline					
All disabled	0.10	0.42	0.70	1.83	0.60
With locomotion disability	0.10	0.42	0.70	1.22	0.58
No aid	0.28	0.45	0.94	1.22	0.68
Crutches	0.42	--	--	0.53	0.47
Cane	0.18	0.35	0.70	1.04	0.51
Walker/Rollator	0.10	--	--	0.52	0.36
Without locomotion disability	0.70	--	--	1.83	1.26
Unassisted wheelchair	1.05	--	--	--	--
Assisted ambulant	0.42	0.52	0.86	1.05	0.69
Assisted wheelchair	0.70	0.96	1.05	1.05	0.96

Table 3.3: Horizontal and incline walking speeds observed by Boyce et al. (1999b).

As can be seen in Table 3.3, there is significant variation in groups, both across mobility impairment and between horizontal and inclined walking speeds. Horizontally, the assisted wheelchair had a mean walking speed that was 0.05 m/s above the average for an individual without a locomotive impairment. In contrast, the unassisted wheelchair demonstrated a 0.36 m/s deficiency in the equivalent comparison. More drastically, the walker/rollator presented a mean speed of 0.57 m/s. This is approximately half that of the individual without a locomotive impairment, and the lowest speed recorded of the group. Yet, the maximum speed of the walker/rollator lies above that of the unassisted wheelchair. In comparison to horizontal walking speeds, the upward incline negatively affected all mean walking speeds. Contrastingly,

the downward incline presented more variability, but remained to negatively affect the majority of mean walking speeds.

Additional impairments that limit the individual's capacity to physically mobilise are outside the scope of this research given their broad and significant variability. This is likely to require a multitude of experimentation to isolate the impact of visual impairment from other impairments. However, future research should consider the recommendations and best practices derived from this thesis in defining capacity, performance, and setting actionable user requirements based on established research. Indeed, disabled populations have differing needs that may not be relevant to the needs of others, yet the fulfilment of which will present widespread improvements for all (Mace et al., 1997). As with the visually impaired population, there is some understanding of these requirements, yet capacity and functional performance remain in need of further research and augmentation.

For instance, in the example from TfL (2015a), step-free access is a critical requirement for wheelchair users, but only 26% of underground stations have step-free access. Consequently, trips using only the step-free network, including buses, take 14% longer than an equivalent journey using all available routes. Travellers with a mobility impairment, which account for 58% of the disabled population, are therefore inherently disadvantaged when step-free access is required. As a result, the average trip rate for these users is 12% lower than that for the entire population (TFL, 2017).

3.2.2. Psychological Factors in Individual Behaviour

It is important to note that concepts of knowledge and cognition are deeply related and interdependent. For instance, a visually impaired person is likely to have encountered stairs throughout their lifetime and will have knowledge of their use. Yet, they may still experience elevated anxiety when traversing a set of stairs, thus impacting their short-term cognitive state (Taylor et al., 2019). This may arise from a fear of falling, as discussed by Wang et al. (2012). Repeated instances of such negative psychological reactions to mobility may then lead to reduced activity and societal interaction, resulting in depression, ill-health, and frailty (Wang et al., 2012; Xue et al., 2008). Such impede on cognitive capacity, preventing the growth of the individual's knowledge and further impeding on their psychological and physiological capacity to mobilise. A cycle of immobility therefore prevails (Xue et al., 2008).

3.2.2.1. Knowledge

In a study involving 10 visually impaired participants, Brouwer et al. (2008) defines 'cognitive mapping' as the formation of object-to-object spatial relationships around an individual. This is a cognitive process that compiles sensory information with the user's tacit (experiential) knowledge of their ability and the environment around them. Indeed, the ability of cognitive mapping is one that is tacitly learnt, adapted, and developed by a visually impaired person. It is a coping mechanism resulting from the reduction in visual memory that exists with visual impairment (Sanchez & Maureira, 2007).

Cognitive mapping is therefore an active process where the individual learns and remembers, using their limits of sensory acquisition of information in their environment. Therefore, in addition to tacit knowledge, a visually impaired individual will seek additional explicit

knowledge of their environment. This is both in planning prior to entering this environment, and in active development within the environment. Ultimately, a better knowledge, and thus cognitive map, of the environment leads to better familiarity with the environment. This results in a more comfortable mobility experience, and an enhanced mobility performance (Samoshin & Istratov, 2014; Sanchez & Maureira, 2007). Tacit and explicit knowledge, including the visually impaired individual's ability to acquire each, are therefore explored.

Congenitally visually impaired individuals are likely to possess an enhanced spatio-cognitive ability relative to adventitiously impaired counterparts (Passini et al., 1990). Passini et al. (1990) concluded this through conducting experiments with participants that were congenitally totally blind, adventitiously totally blind, or possessed weak residual sight. A sighted and a sighted blindfolded group served as a control, and 18 participants per group, matched for age (18-65 years old), education (secondary to postgraduate) and gender (equal distribution), were observed.

Participants were asked to conduct three sets of tasks (8 total subtasks) in a 'labyrinth' environment, each corresponding to an increasing level of spatio-cognitive structure, comprising:

1. Wayfinding – Learning a route, inversing route, combining routes, transfer of scale
2. Pointing to distinctive locations within a journey, finding shortcuts, making mental rotations of the journey
3. Reproducing the overall layout by discovering spatial organisational principles such as symmetries.

The percentage of successful completion of each task without errors is shown in Table 3.1 (Passini et al., 1990) to support the following conclusions. It can be seen that the sighted group is the best performing, followed by the group with residual sight in almost all tasks. This suggests that enhanced spatio-cognitive processing remains inferior to enhanced sensory capacity. Remarkably, the congenitally blind group completed 48.6% of the tasks with relatively equal performance across tasks, performing better than the adventitiously blind and blindfolded control groups in the majority of tasks.

	Congen. Blind	Advent. Blind	Visual Residue	Blind-folded	Sighted	Average Score	L
Tasks							
1 Learning route	94.4%	53.8%	94.4%	44.4%	100.0%	77.4%	
2 Inversing route	38.9%	7.7%	61.1%	44.4%	78.8%	46.0%	
3 Combining routes	38.9%	15.4%	72.2%	33.3%	78.8%	47.5%	
4 Changing scale	50.0%	53.8%	33.3%	55.6%	50.0%	48.5%	
5 Pointing	55.6%	38.5%	100.0%	16.7%	94.4%	61.0%	
6 Shortcut	38.9%	15.4%	83.3%	22.2%	94.4%	50.8%	
7 Rotating	22.2%	30.8%	16.7%	16.7%	33.3%	23.9%	
8 Coordinating	50.0%	46.2%	66.7%	27.8%	77.8%	53.7%	
Average Score	48.6%	32.7%	61.8%	32.6%	75.7%	50.3%	

Table 3.4: Percentage of successful completion of spatio-cognitive tasks in Passini et al. (1990).

These findings suggest that visually impaired individuals have tacitly developed an enhanced ability to process and act on spatial information. This is true across all levels of the spatio-cognitive structure proposed by Passini et al. (1990), and this can enhance mobility capacity beyond the limits of sensory capacity. Furthermore, Passini et al. (1990) attributes up to 10% of the difference in successful completion to age and education each, with performance increasing as education increases or age decreases. This, however, is a marginal difference. Further testing of differently aged and educated visually impaired individuals is therefore required to confirm this relationship.

In summary, research into visually impaired mobility should distinguish physiological sensing from tacitly developed cognitive processing when attempting to understand mobility capacity. This is especially in participants with induced impairments that are likely to produce limited performance when compared to their congenitally impaired counterparts. Bradley and Dunlop (2005) found this discrepancy when investigating whether a group of sighted participants and a group of visually impaired participants experience a difference in mental and physical demands. This is when given two different sets of verbal instructions directing them to four landmarks. Likewise, May (2000) concludes that there should be consideration for mental imaging capacity of congenitally blind individuals, specifically how environmental information is acquired, learnt, processed, and used.

Passini et al. (1990) demonstrates a well-controlled and balanced sample selection given that groups were matched according to several factors. Moreover, individuals with severe psychological impairments were excluded (although psychological impairments should be explored in future work to ensure a truly heterogenous population). Additionally, a key finding in the experimental method by Passini et al. (1990) is the distinction and testing of different 'levels' within the tacitly developed spatio-cognitive process. This suggests that there is a hierarchy to how a visually impaired individual processes and organises the explicit knowledge they obtain, thus controlling the construction of their cognitive map.

Indeed, Sanchez and Maureira (2007) contextualises this by conducting a trial using 10 blind participants, aged 20 to 32 where each had to traverse a digitally generated subway station with various prompts in space and time. Firstly, it was apparent that lack of knowledge about certain aspects of a mass transit system is a hindrance on the spatial awareness and cognitive mapping of the transport user. Moreover, Sanchez and Maureira (2007) suggests that, to obtain a comprehensive knowledge of a transport network, the user must first have a good understanding of fundamental network features, such as underground lines, platforms, and stations. The user must then comprehend the specifics of a given local network, such as the name of the station, its location and surroundings, and the names of lines that determine a route. Finally, efficient use of the network is achieved via the amalgamation of various concepts and knowledge learned by the user. This includes better planning and appreciation of cost. It was also concluded that consistent prompts, and thus acquisition of knowledge, aided cognitive mapping.

Strothotte et al. (1996) presents similar findings of structured knowledge through interviews with visually impaired individuals and mobility trainers. This aimed to determine the user requirements of an outdoor navigation system. All users consistently expressed a desire to control the flow of information with the ability to request more or less depending on the operational scenario in which they find themselves. This can range from detailed guidance to

reassurance that the correct route is being followed. The different levels proposed are as follows:

1. Level 1: Basic information to ascertain whether or not user is still on track, including obstacles and crossings.
2. Level 2: Detailed information to be selected for inclusion in journey, such as shop names and nearby landmarks.
3. Level 3: Transport information, such as nearest bus stop, rail, or telephone.

Indeed, the effectiveness of structured knowledge was observed by Strothotte et al. (1996) in testing the navigation system with participants aged between 25 and 61 in Berlin. It was found that the ability to control the flow of information assisted spatial awareness. Moreover, feedback received showed that exact distance directions were preferable, such as "After 132 meters on your right, there is the institute of computer science".

As well as structuring knowledge, Bradley & Dunlop (2004) suggests the existence of a relationship between an individual's desired knowledge and their physiological capacity and operating environment. Bradley & Dunlop (2004) observed 15 participants aged between 27 to 74 years to walk to three predetermined indoor (university building) and outdoor (city centre) landmarks. Individuals were instructed to ask questions whenever needed to navigate and orientate. Each route required approximately 5 minutes to reach the landmark, allowing for good data collection time. Visually impaired participants were discretised into those experiencing a loss of central vision (CV), loss of peripheral vision (PV), and total vision loss (blind).

Significant differences were found between groups relating to information requirements, and the environmental cues encoded and used to orientate and navigate. In outdoor environments, the blind group asked questions about environmental cues not asked for by others, including side streets, steps, doors, tactile markings, wind direction. This group also asked more about distances and had a greater reliance on auditory reference points. The PV vision loss group asked the least questions in fewer categories, and used distant landmarks to orientate such as signs, other pedestrians, and traffic. This group also typically had much more usable sight in daytime conditions relative to night-time. The CV loss group asked the most for signs and traffic lights, and used light and dark areas to orientate.

In indoor environments, the PV loss group asked more questions than when operating outdoors, with the largest increase in the number of questions asked relative to other groups. Some questions increased proportionally for all groups, such as questions on distances by the blind group. The CV loss group used environmental cues in greater proportion, increasing reliance on light/dark areas. This resulted from the indoor environment presenting a richer and more rapidly changing environment relative to the outdoors. It can therefore be concluded that knowledge that is meaningful to one form of visual impairment is incidental to another, and that future research should aim to make clear discretisation in its testing groups and environments to control this.

Additionally, Bradley & Dunlop (2004) presents an important conclusion in that visually impaired individuals actively seek and update their knowledge. Indeed, Loomis et al. (2001), in designing a GPS-navigation system for visually impaired users, suggests that human navigation is founded on updating one's position and orientation. This involves position-based

navigation, velocity-based navigation, and acceleration-based navigation. An active and relativistic knowledge of the immediate environment and its obstacles is desired, as well as locating the destination beyond the immediate environment. Loomis et al. (2001) finds that the biggest challenge to visually impaired subjects surveyed is lack of knowledge on distant landmarks, heading and self-velocity.

Moreover, Loomis et al. (2001) explains that actively seeking knowledge of one's environment occurs both when the individual is static and mobilising. This is summarised in the following concepts that form the fundamental knowledge required for wayfinding:

1. Heading: Facing direction of the traveller's body or head with respect to reference direction (e.g., true north). This is also defined when the traveller is stationary.
2. Course: Traveller's direction of motion relative to reference direction. This is only when the traveller is in motion.
3. Bearing: Direction from traveller to another point in space relative to reference direction. A traveller wishing to travel to a certain point will set a course equal to the bearing of that point.
4. Relative bearing: Bearing of a location with respect to the course of the traveller.

As well as seeking explicit knowledge of an environment, such knowledge can be tacitly gained by the user through repeated movement and interaction with their environment. This could have a much greater and more consistent performance impact on mobility than that obtained via non-recurring visual and auditory reference points. Such was discovered in experiments by Wright et al. (1999) and Sorensen and Dederich (2015). Wright et al. (1999) investigated the effects of six differently illuminated wayfinding systems on the evacuation ability of 30 differently visually impaired and 6 normally sighted participants (individually) (further explored in Chapter 6). Sorensen and Dederich (2015) observed the evacuation of 40 differently visually impaired participants (in groups) in 2 and 3-storey buildings. Both studies measured participants' horizontal walking speed and the rate of descent on stairs.

In Wright et al. (1999), irrespective of the wayfinding system tested, traversing the staircase appeared to consistently yield the greater performance relative to horizontal walking speed. A similar phenomenon was observed in Sorensen and Dederich (2015). To highlight this, the following table (Table 3.5), adapted from Sorensen and Dederich (2015), displays speeds obtained within the experiment. Note that visual impairments in Sorensen and Dederich (2015) were categorised into group A, B, C, and D, according to the Danish national system, where A represents the least severe visual impairment, and D represents total blindness. As evacuees in A and B were not recorded descending stairs, Table 3.5 only displays the speeds obtained for groups C and D when walking horizontally and descending stairs.

Category	Mean (m/s)	Min (m/s)	Max (m/s)	Std Dev (m/s)
Horizontal Walking Speed				
C (n=8)	0.95	0.38	1.56	0.30
D (n=6)	0.75	0.35	1.09	0.22
Speed Descending Stairs				
C (n=3)	0.74	0.54	0.92	0.10
D (n=4)	0.71	0.58	0.91	0.09

Table 3.5: Horizontal walking speeds and stair descent speeds observed for visually impaired evacuees (Sorensen & Dederich, 2015).

The results obtained by Wright et al. (1999) under normal lighting are compared to the study by Sorensen and Dederich (2015). This is as the latter study did not specify the use of additional wayfinding systems or alterations to the normal lighting present within the testing environment. Both studies demonstrated very similar mean descent speeds for stairs, differing at most by 0.06 m/s when comparing the mean descent performance of group D (0.71 m/s) to the mean descent speed obtained by Wright et al. (1999) of 0.77 m/s under normal lighting. Additionally, the standard deviations observed for both group C and D when descending stairs are significantly smaller than those obtained for their respective horizontal walking speeds. This therefore suggests a more consistent performance when descending stairs, a similar observation made by Wright et al. (1999).

From the comparative analysis, it can therefore be hypothesised that a repeated motion, such as descending stairs, serves to orientate the visually impaired pedestrian. Indeed, this is corroborated when comparing across groups of visual impairment in Sorensen and Dederich (2015). Here, the percentage difference in mean descent speed between group C and group D is 4.1% (1 d.p.), which is notably smaller than the 21.1% (1 d.p) percentage difference between the mean horizontal walking speeds of the two groups. Similarly, the percentage difference in the standard deviations of the descent speeds between group C and group D is 10%, which is also smaller than the 26.7% (1 d.p.) percentage difference between the standard deviations of the horizontal walking speeds of the two groups.

Consistency in repeated motion was also observed by Wright et al. (1999). When compared to the performance of the normally sighted participants, the visually impaired participants were able to achieve 45-70% of their speed when walking horizontally, and a more consistent 75-80% of normal speed when traversing the staircase. Furthermore, it was noted that the repeated pass, regardless of wayfinding system used, was typically faster than the first pass. This demonstrates an acquired knowledge of the environment through a repeated physical and cognitive process, regardless of the visibility of the surrounding environment.

Additionally, Wright et al. (1999) noted hesitation in participants when trying to find the first step in the staircase and when traversing a landing. Similarly, Feghali (2018) noted this hesitation in different visually impaired participants approaching foam steps of unknown location. This suggests that, while a repeated process is beneficial to mobility, an anomalous event or obstacle can have an equally detrimental impact on the visually impaired user's confidence and, ultimately, mobility.

The comparison between these two studies is imperfect as other evacuees where present in Sorensen and Dederich (2015), whereas Wright et al. (1999) tested each participant individually. Sorensen and Dederich (2015) therefore noted additional crowd interactions such as instances of evacuees assisting one another. This may therefore explain the relatively higher horizontal walking speeds observed by Sorensen and Dederich (2015) when compared to those from Wright et al. (1999). Further experimentation is therefore required to conclusively understand how the interactions of crowds may affect the mobility of the visually impaired.

Regardless of this limitation, it can be concluded that repeated and anomalous events should be discretised and noted in all experimentation attempting to determine the mobility capacity of visually impaired individuals. This then translates to effective performance as a realistic environment, such as a transit station, presents their users with several dynamic obstacles and reference points. These are often complex and can include such features as varying

illumination, pedestrian congestion, and inconsistent physical infrastructure (Norgate, 2012; Strickfaden & Devlieger, 2011). These can impact cognitive mapping and are explored in Chapter 6.

Finally, Samoshin & Istratov (2014) conduct novel data collection and experimentation that quantifies the impacts of knowledge, familiarity, and cognitive mapping on visually impaired evacuees. Particular attention is therefore given to this study and its results are independently analysed. Questionnaires were returned by 201 visually impaired individuals in Russia where 17.3% were completely blind and the remainder possessed varying degrees of useable sight (according to classification by Russian medical legislation). The testing sample was relatively balanced, with 68.2% being over 40 years and an approximately even split between male and female (50.2% male). Four sets of themed questions were proposed and the results from Samoshin & Istratov (2014) are interpreted and summarised as follows:

Set 1 – Evacuation Training:

I. 12% were not familiar with general requirements of fire safety
II. 92.5% received at least some special fire training
III. 69.6% participated in evacuation drills

The results show that the majority has had at least some extra training and awareness. It is therefore hypothesised that the sampled individuals should have a principal understanding of evacuations, forming the first level of explicit knowledge required for effective knowledge as suggested by Sanchez and Maureira (2007).

Set 2 – Firefighting and defence

I. 50.3% would not attempt to extinguish fire
II. 8.6% would not call the fire department
III. 52.8% would not turn on a warning system
IV. 47.5% would not organise the evacuation

There appears to be a divide in how visually impaired people would participate in the evacuation. This study is limited in that a normally sighted control group was not used. Therefore, conclusions on how visual impairment and knowledge affects firefighting and defence cannot be reliably formed. However, it was noted that the visually impaired individuals with the most severe visual impairments are knowledgeable on their vulnerability in fire, explaining that they would be 'confused/scared/remain in place'. Such suggests that knowledge (evacuation training in this case) does not necessitate a more active mobility by the individual. Rather, knowledge could demotivate the individual, highlighting their vulnerability and triggering adverse psychological feelings.

Set 3 – Elevators and refuge areas

I. 32.1% would not use an elevator in an evacuation
II. 29.7% would not use refuge areas in an evacuation

Notably, individuals that would not use an elevator attributed their decision to safety stigmas in older elevators. They were unaware of the enhanced safety of newer elevator designs. This finding demonstrates that higher level knowledge, described by level 2 in Sanchez and Maureira (2007), does impact the individual's use of environmental elements and can consequently hinder their safety. Additionally, individuals that would not use a refuge point

associated this with accessibility challenges in navigating through a building. It is unclear if regional physical accessibility standards in Russian buildings bias this result, although this finding connotes a further loss in safety and environmental interaction.

Set 4 – Familiar versus unfamiliar routes

I. 81.3% could self-evacuate using a familiar route.
II. 39.7% could self-evacuate using an un-familiar route.

This is the most explicit questionnaire result in comparing knowledge and mobility capacity. It is evident that familiarity with a route can significantly increase visually impaired individuals' self-perceived ability to mobilise and evacuate. Ultimately, familiarity is found to require knowledge across all levels of the spatio-cognitive structure (Passini et al., 1990; Strothotte et al.,1996; Sanchez & Maureira, 2007).

Samoshin and Istratov (2014) proceeds to quantify the impact of familiarity in mobility capacity, conducting an evacuation with 51 participants with varying severity of visual impairment. In one large group, participants egressed a route which was familiar and a route that had unknown characteristics. Average walking speed on a horizontal section in a familiar and unfamiliar route was found to be 0.83 m/s and 0.44 m/s, respectively. Similarly, average walking speed when passing through doorways in a familiar and unfamiliar route was found to be 0.54 m/s and 0.36 m/s, respectively. In addition to the positive psychological impacts found in the questionnaire results, this evidences that familiarity translates to a measured, functional impact on mobility capacity.

Samoshin and Istratov (2014) presents limitations in that mobility was only conducted under group performance, and this is likely to influence the individual walking speeds observed. Moreover, familiarity is difficult to quantify, and it is uncertain as to how familiarity was effectively obtained across all participants. However, the significant difference in measurements obtained between familiar and unfamiliar routes suggests that the conclusions derived remain qualitatively valid. This is supported by the video recordings and statistical analysis conducted by Samoshin and Istratov (2014).

3.2.2.2. Cognitive State

From research conducted by Taylor et al. (2019) and Xue et al. (2008), there occurs a short-term and long-term effect on the cognitive state of the visually impaired person directly resulting from mobility. This is that fluctuations in the visually impaired person's cognitive state can occur in daily mobility scenarios. These can compound over time to an overall shift in the long-term cognitive state of that individual, such as in the experience of long-term depression. It is therefore important to first assess the extent of these short-term impactors on cognitive state and their fundamental correlation to visual impairment.

Taylor et al. (2019) conducted an experiment investigating dynamic levels of self-perceived anxiety and concern in 30 participants with varying degrees of dry AMD, from early stage to Geographic Atrophy (GA). Visual acuity and contrast sensitivity were recorded for each participant. The experiment involved participants watching approximately 30 minutes of video showing typical mobility scenarios, being asked to press a button while watching if they felt elevated concern or anxiety. Taylor et al. (2019) concluded that those within the later stages of

AMD are more likely to experience such negative psychological changes, but this could not be correlated with visual function.

Interestingly, traversing stairs and walking across a cliff-edge, as well as map-reading were the most impactful on participants. This is expected given the good acuity required for map reading, and the elevated fear of falling that older adults may experience (Wang et al., 2012). The study is limited in that video-based testing could dilute the cognitive impacts a participant could experience in the real-world. This is especially as such laboratory testing eliminates the participant's perceived physical risk, as well as the additional cognitive processes in decision making and orientation required in reality (Sanchez & Maureira, 2007).

Additionally, viewing a video on a fixed screen may eliminate certain eye movements while failing to represent how the individual's visual field realistically operates. This has been shown to impact mobility (Turano et al., 2004). However, this study remains important in highlighting the increasing short-term cognitive impacts that could be experienced by older adults with later-onset visual impairments.

While Taylor et al. (2019) highlights moments of stress in mobility, Turano et al. (1998) demonstrates a continuous added mental effort required during walking. This was achieved via the employment of a dual-task methodology investigating walking speed and reaction times of 13 patients with RP and 29 normally sighted people. Participants were instructed to traverse a simple and complex route. Patients with RP were shown to require more mental effort to navigate the complex route in comparison with the normally sighted group. Furthermore, Turano et al. (1998) highlights a covariance between losses in visual field and contrast sensitivity, and elevated mental effort in walking.

Contrarily, Haymes et al. (1996) did not find a significant correlation between psychological variables and mobility in the RP patients. However, the studies varied in that Turano et al. (1998) employed a control route versus the indoor retail space used in Haymes et al. (1996). Additionally, Turano et al. (1998) observed novel short-term psychological variables through the use of reaction times during mobility activity. Such asserts the existence of short-term psychological variables (such as mental effort) with longer-term psychological variables that may not be immediately visible. These include personality traits and intelligence and are shown to impact visually impaired orientation and mobility (Haymes et al., 1996; Beggs. 1991).

Beggs (1991) attempts to quantify how longer-term psychological factors can impact mobility. A study group of 71 clients from a rehabilitation course were selected, each having a form of visual impairment. Each possessed at least minimal outdoor mobility and spoke English as a native language. Participants were asked to traverse a very quiet suburban street with typical street furniture such as lampposts, trees, and driveway openings. Two passes were conducted to find actual walking speed and preferred walking speed, respectively. A questionnaire with a 5-point scale was administered to each between the passes with words associated with feelings towards mobility. These were as follows (Table 3.6):

Scale Minimum	Scale Maximum
Anxious	Not anxious
Observant	Not observant
Unwary	Wary
Confused	Not confused

Safe	Not safe
Do not stand out	Stand out
Incapable	Capable
Relaxed	Not relaxed
Alert	Not alert
Cautious	Not cautious
Disorientated	Not disorientated
At risk	Not at risk
Unselfconscious	Self-conscious
Things under control	Things not under control
On your guard	Not on your guard
Not concentrating	Concentrating
Careful	Not careful
Sure of your surroundings	Not sure of your surroundings
Vulnerable	Not vulnerable
Conspicuous	Not conspicuous
Self-confident	Not self-confident

Table 3.6: Words associated with feelings toward mobility employed by Beggs (1991).

According to Beggs (1991), different words in Table 3.6 had a different significance to mobility. These were, in order of least to most significant, 'disorientated', 'on your guard', 'confused', 'things out of control', and 'incapable'. All words strongly refer to confidence and self-efficacy. The lattermost term, 'incapable', may indicate the most significant physiological feeling impacting visually impaired mobility. Beggs (1991) proceeds to conclude that visual function was poorly correlated with changes in walking speed. Rather, it is suggested that visual function was perhaps only indirectly correlated with walking speed as a result of its impact on feelings toward mobility (which then directly impacted walking speed). This is a significant finding as it challenges preceding conclusions on visual function being the primary indicator of mobility.

The conclusion that mobility activity may be governed by psychological decisions from the visually impaired individual was first suggested by Clark-Carter et al. (1986a; 1986b). From Beggs (1991), these decisions would arise from the individual's confidence and self-efficacy, regulating walking speed to improve their immediate psychological well-being and to mitigate feelings of confusion and loss of control. Feghali (2018) observed this behaviour during the mobility testing of an older experimental participant with glaucoma through a mobility course at PAMELA at differing lighting levels. The participant displayed sudden and unexpected feelings of fear when asked to use their worse eye to traverse the course. The participant explained that they had not realised the extent of their vision loss when only using this eye. Continuous hesitation was noted with sporadic pauses as mental stress presided over visual function in controlling mobility, even when traversing a simple straight section with no obstacles.

Indeed, literature observing psychological orientation and the mobility of visually impaired people support this notion of self-efficacy regulating mobility. Seybold (2005) enhances this conclusion by distinguishing those who are born with severe visual impairments to those who acquire vision loss throughout their life. It is suggested that acquired vision generates unique feelings of confusion. This is as those with vision loss may not appear to have a disability and therefore struggle to adapt given the transition from a normality that they would have been

previously accustomed to. Indeed, loss of sight deprives those of the feedback mechanisms that they would typically rely on, intensifying their awareness of other's feelings towards them and motivating self-isolation (Dodds, 1993; Dodds, 1988). Such equally invokes negative reactions in sighted people, snowballing segregation, distancing, and an ultimate loss in self-efficacy (Smith, 1997).

Dodds (1993; 1998) suggests a longer-term psychological approach to effective mobility training. This involves primarily addressing feelings towards visual impairment and inspiring confidence and self-worth in the individual. This expands on orientation and mobility training for visually impaired people which previously emphasised technical ability and knowledge acquisition. These conclusions are compounded in research conducted by Soong et al. (2001). Here, no immediate improvements in mobility were noted in a visually impaired group that received mobility training versus a control group that did not receive training. Visual function including visual acuity, contrast sensitivity, and visual field were accounted for. This suggests that mobility is primarily governed by long-term cognitive processes, and that research must observe the manifestation and development of such in an individual as they transition through visual impairment.

These long-term processes governing mobility are likely to correspond to the adjustment to blindness determined by Tuttle and Tuttle (1996), especially in acquired visual loss during later life as discussed by Seybold (2005). This begins with Trauma (Physical or Social) where the visually impaired person becomes overwhelmed with knowledge of their sight loss, the intensity of which corresponding to '(1) the significance of the loss to the individual, (2) the suddenness or unexpectedness of the event, and (3) the degree of visual loss' Tuttle and Tuttle (1996) (p.144).

This is followed by Shock and Denial, and then Mourning and Withdrawal. Here, functional performance losses become exacerbated, and the individual may withdraw from activities of daily living. Succumbing and Depression succeed this, but the following stages of Reassessment and Reaffirmation, Coping and Mobilization, and Self-Acceptance and Self-Esteem are when a positive shift occurs. Here, the individual relearns and regains their purpose in life. These psychological states concur with (Beggs, 1991). The correlation of self-driven feelings of incapacity with declining functional mobility is therefore corroborated, as are self-confidence and self-efficacy in increasing functional mobility.

On reflection to Soong et al. (2001), changes in mobility performance were measured immediately after early intervention (mobility training). It is therefore plausible that the psychological state of the participants fell into the beginning stages of Tuttle and Tuttle's (1996) adjustment process. Measured mobility may have consequently been limited by this long-term psychological process, more so than short-term intervention.

Finally, attention should be given to cognitive impairments arising from certain neurological, non-ocular conditions that also result in visual impairment, as suggested by Rahi & Cable (2003), Gilbert et al. (1999), Black (1982), and Martin et al. (2016). The profoundness of cognitive impairment in affected individuals, such as children diagnosed with severe brain trauma, will have mobility that is likely limited by their cognitive capacity and educational development. This, however, is outside the scope of this research given the scarcity of mobility research on visually impaired children, especially those with cognitive impairments.

In summary, both the short-term and long-term cognitive state of visually impaired individuals should be considered when conducting mobility research. Long-term cognitive state is likely to dominate the individual's ability to perform activities of daily living, the ultimate goal of functional performance. Contrastingly, short-term cognitive state can include rapid fluctuation in mental effort when navigating challenging environments. Artifacts of long-term state are then likely to interfere with how the individual reacts to short-term changes in state. For instance, the effectiveness of coping with increased cognitive effort when mobilising as a result of depression.

3.3. Observing the Mobility of Visually Impaired People from Group Behaviour

3.3.1. Physiological Factors in Group Behaviour

Research exists to demonstrate behavioural changes in both the individual and crowd in mobility scenarios (Moussaid et al., 2011; Rio and Warren, 2014; Hoogendoorn & Daamen, 2005). Physiological constraints can often dictate such observations, and these pertain to all pedestrians acting in a crowd, regardless of ability. Indeed, as discussed by Gorrini et al. (2013), crowds can contain high densities, leading to a reduction in each pedestrian's freedom for spatial positioning. Distinctive crowd behaviours can therefore form, such as turbulence, self-organisation into coupled formations, and competitive interactions between individuals. Such behaviours arise from the individual's need to avoid physical contact with other members of the crowd, essentially acting as mobile obstacles with a repulsion effect. Additionally, each individual may wish to form and maintain group cohesion with familiar members or subgroups to facilitate social interactions. This is a cognitive process limited by physical constraints (Gorrini et al., 2013).

Considering visual capacity, sufficient awareness of other individuals within the crowd is required for the individual to effectively deploy these behaviours. Simply, this is predominantly accomplished with the use of sight, leading to phenomena such as visual coupling. As discussed by Rio & Warren (2014), visual coupling is the impact on one individual's behaviour within the crowd resulting from the visual detection and formation of dependencies with the individuals around them.

Rio & Warren (2014) found that the strength of this coupling is dependent on the eccentricity of the individuals involved. Moreover, an individual can visually couple with multiple individuals. It can therefore be hypothesised that a reduction in the individual's usable sight may lead to a delay in, or a reduction to, their ability to detect individuals around them. This could greatly alter the individual's ability to depict these in-crowd behaviours, including their capacity to effectively visually couple with neighbours. In turn, this may also lead to more drastic effects on the behaviour of the entire crowd.

Therefore, in the context of visual impairment, physiological factors affecting crowd mobility can be initially characterised by the capacity to detect the crowd and the physical forces from the crowd. These are factors that closely interact, and each is explored through a 'top-down' approach where the physical formation of the crowd as a whole is first investigated. This is followed by investigating the heterogeneity and homogeneity of a crowd, its impacts, and the underlying physical factors arising from the inclusion of visually impaired individuals. Finally, the psychological processes employed by the visually impaired individual in a crowd are investigated.

Firstly, in considering the motion of a crowd as a whole, it is a large moving mass that may be constricted by the dimensions of its environment. This is applicable to both heterogenous and homogenous crowds. Hoogendoorn & Daamen (2005) visualises this through a study of bottlenecks where pedestrian traffic demand exceeds capacity, a phenomenon influenced by such factors as bottleneck width, wall surface, and pedestrian behaviour at the bottleneck.

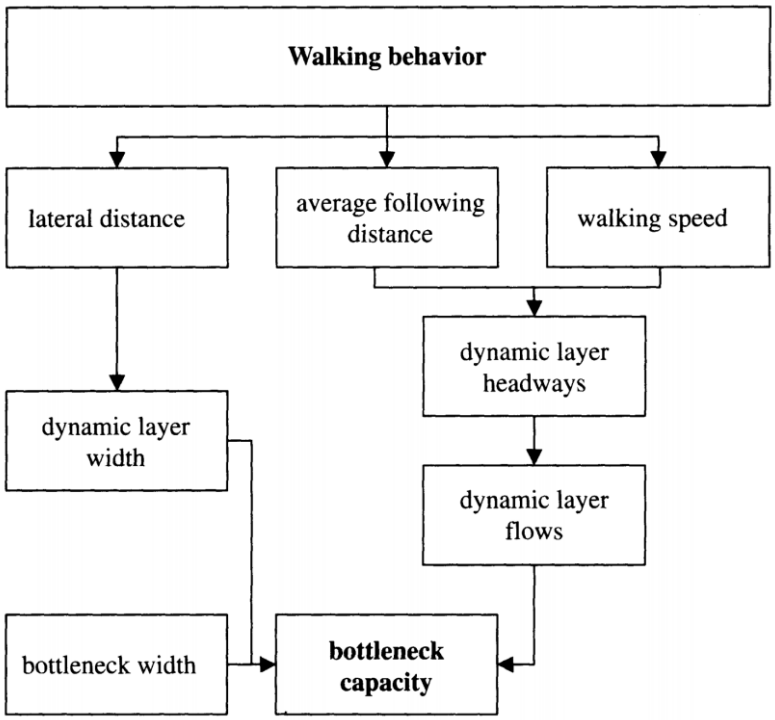


Figure 3.3: Causal diagram of factors affecting flow levels and flow distributions (Hoogendoorn & Daamen, 2005).

Figure 3.3 is a causal diagram of factors affecting flow levels and distribution, derived from experimentation conducted by Hoogendoorn & Daamen (2005). Pedestrians inside bottlenecks effectively form layers or trails, with potential for the distance between these lying below the width of a single person. Overlapping layers are a phenomenon referred to as the "zipper" effect; within each layer, pedestrians visually couple with and follow one-another, with wider bottlenecks forming more layers.

Fundamentally, each factor affecting flow levels also affects the density and velocity of the group and each member. Through critical review of 25 studies, Weidmann (1992) illustrates the empirical relationship between density and velocity in Figure 3.4. The individual domains segmenting this relationship reflect different decreases in velocity, triggered by shifting causal factors within the group.

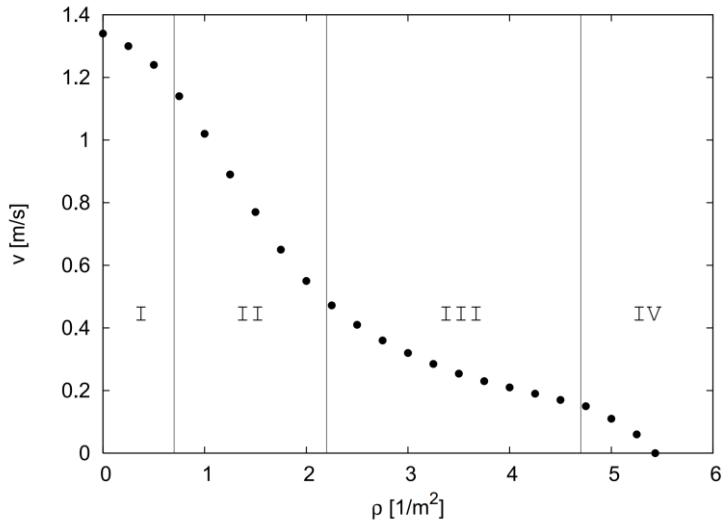


Figure 3.4: Empirical relationship between density and velocity (Weidmann, 1992).

Density increases can be caused by additional group members or changing environmental constraints. The presence of each domain suggests that the density growth in a group is not a simple, linear effector on velocity. Instead, there exists a decline in the individual's ability to determine their velocity as density increases, allowing the group's velocity to dominate. Table 3.7 summarises each domain as interpreted by Weidmann (1992).

Domain	ρ (1/m^2)	v/ρ Profile	Causal Factors
I	$\rho < 0.7$	Small but increasing decline	Individual free velocity dominates allowing for passing manoeuvres (causing velocity decrease)
II	$0.7 \leq \rho < 2.3$	Nearly linear	Available space reduces (passing manoeuvres of slower pedestrians not feasible) and individual control of velocity is restricted; negligible internal friction in unidirectional streams as available space is sufficiently large to avoid contact with other pedestrians
III	$2.3 \leq \rho < 4.7$	Curving and no longer linear	Further space reduction leading to unavoidable contact between pedestrians; internal friction increases from domain II but reductions in velocity diminish
IV	$\rho \geq 4.7$	Rapid decline	Strongly restricted space; internal friction likely determining factor and pedestrians behave like hard bodies as maximal density reached

Table 3.7: Domains representing shifting velocity/density relationships in a group (Weidmann, 1992).

It is noted that this graphical relationship is an approximation, and that certain scenarios could lead to unexpected fluctuation. This includes densities exceeding 5.4 persons/m^2 in fire escapes (Togawa, 1955). Moreover, internal friction is expected to vary according to the directionality of the group flow. This is demonstrated in comparing the single-file groups flows observed by Seyfried et al. (2005), unidirectional flows in Seyfried et al. (2009), and opposing flows in Hoogendoorn & Daamen (2005) and Lam et al. (2003).

A critical generalisation made by this relationship of velocity and density is that the velocity is assumed to be at a maximum when density is at its lowest. This implies that the individual can

only achieve their maximum preferred walking speed when operating individually, without the influence of the group. Simply, the addition of a crowd is assumed to generate a negative impact on the individual's mobility, primarily driven by reduced space and internal friction.

However, Hoogendoorn & Daamen's (2005) brings forth a primary physiological consideration when investigating crowd behaviour in the context of visual impairment and heterogenous populations; this is the physical force from the crowd and its causal factors, including walking speed, lateral distance, and average following distance. These build on the theory of visual coupling discussed by Rio and Warren (2014), and are reliant on the visually impaired individual's capacity to detect the crowd.

A visually impaired individual can therefore experience unique forces according to their visual function and individual mobility, altering or exceeding simple internal friction. Sharifi et al. (2016) explores this through conducting an experiment. This involved 332 participants egressing passageways of varying widths with dynamic turning angles (right and oblique), stairwells, and bottlenecks at their maximum safe speed. 16 visually impaired pedestrians participated in this study, aged between 18 and 80 years old.

Horizontal walking speeds for visually impaired participants were found to be 12% slower than those of their normally sighted counterparts. Sharifi et al. (2016) also demonstrates that visually impaired participants maintained a large headway from other visually impaired participants. This contrasts the shorter headway seen between normally sighted participants and visually impaired participants. The hypothesis testing conducted by Sharifi et al. (2016) translated these observations into variations on crowd performance, as suggested by Hoogendoorn & Daamen (2005). It was concluded that a heterogenous population involving disabled people, including visual impairment, results in a 23% lower mean speed relative to a homogenous population.

A shortcoming of this study was lack of discretisation and assessment of visual impairment. Notwithstanding this, the inclusion of these participants indicates that visual impairment, in general, could impact factors determined by Hoogendoorn & Daamen (2005). The use of video recordings and automated tracking software does also imply a robust data collection methodology.

In summary, the dynamics of layer headways and flows appear fundamental in dictating the physical forces on individuals in the crowd, regardless of heterogeneity. These can be dependent on individuals' ability to detect the crowd. They may also act in addition to the internal friction forces responsible for Weidmann's (1992) relationship between velocity and density. Therefore, this relationship cannot be assumed for a visually impaired person without novel experimentation. Furthermore, this must be considered in different flow types given the corresponding and significant variations in crowd dynamics that can occur in unidirectional and opposing flows.

3.3.1.1. Unidirectional Flows

Unidirectional flows constitute crowd motion in a similar relative direction without oncoming or rapid shift in flow direction. Here, pedestrians can arrange themselves in different formations as described by Moussaid et al. (2010) and Figure 3.5. According to increasing density and environmental constraints, pedestrians can walk in a line-abreast, V-like, or river-like formation. Discretising between formations in a unidirectional flow is important as each

constitutes microscopic pedestrian behaviour yielding macroscopic impacts on the crowd's motion. The current understanding of these includes lockstep in single-file flows (Seyfried et al., 2005), stop-and-go waves in wider unidirectional flows (Moussaid et al., 2011), and lane formations of internal unidirectional flows in opposing flows (Helbing et al., 2002).

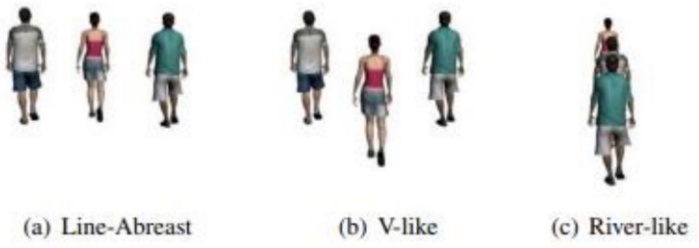


Figure 3.5: Pedestrian formations in unidirectional flows (Moussaid et al., 2010).

The formations presented by Moussaid et al. (2010) can be assumed to provide a good basis of understanding for the general characteristics of a unidirectional flow. This is as video recordings of 1,500 pedestrian groups were analysed in public areas, presenting realistic operational scenarios. The data sample is large, increasing likelihood of a heterogenous population comprising pedestrians of varying mobility, including those with visual impairments.

A shortcoming of this data sample is that it does not allow for a rigorous analysis of each pedestrian's mobility and its corresponding effect on pedestrian formations. However, the review of video footage (and other big data) of public behaviour in realistic operational scenarios remains critical in discovering the presence of these behaviours. Indeed, Seyfried et al. (2009) found similar formations in smaller samples through investigating unidirectional flows of up to 60 pedestrians through bottlenecks (Figure 3.6). These corroborate the formations from Moussaid et al. (2010) at the flow cross-section, and the zipper effect proposed by Hoogendoorn & Daamen (2005) along the length of the flow. It is also suggested that narrower environments influence such self-organising formations.

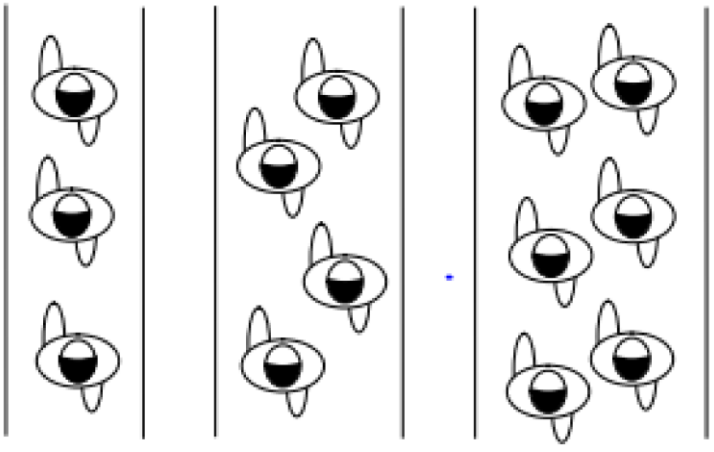


Figure 3.6: Pedestrian formations in varying path widths in Seyfried et al. (2009).

A simple unidirectional flow is a single-file flow compromising the river-like formation, as investigated by Seyfried et al. (2005). In this study, the relationship between density and velocity was observed as one to 34 non-visually impaired individuals (N) traversed a walking track in the shape of a closed loop with perimeter of 13.8 m. Six runs of the experiment were

conducted (N = 1, 15, 20, 25, 30, 34) and data capture was through video recording using both a standard and 'Bumblebee' camera system (a form of stereo vision camera compatible with automated software data analysis of pedestrian movement). The mobility outcome measure was a manual calculation of the time required for each individual (i) to enter (t_i^{in}) and exit (t_i^{out}) the measured section of the loop, as shown in Figure 3.7. Velocity and density can be sufficiently calculated from these measures given the singe-file characteristic of the flow tested.

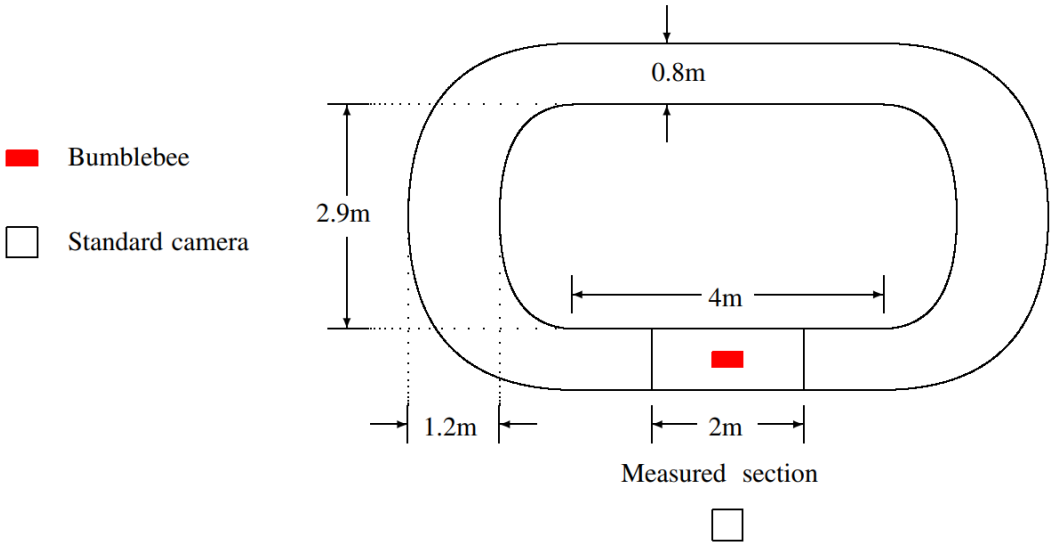


Figure 3.7: Experimental setup for single-file flow observation in Seyfried et al. (2005).

This experimental setup employs both manual and automated data collection to cross analyse and confirm results. Furthermore, Seyfried et al. (2005) address the dimensions of the walking path by ensuring a path width that does not obstruct arm movement, and curvature that is not too narrow to cause sudden changes in flow direction. However, the longest straight section (4 m in length) and recording section (2 m in length) are small. Moreover, instructions to participants not to hurry and omit passing led to a more relaxed movement that may underestimate walking dynamics in realistic operational scenarios. Future studies should subsequently observe the language and intent of walking instructions to participants when testing group flows. This may include incorporating scenarios with both 'restricted' (low stress, passing discouraged) and 'unrestricted' (high stress, passing encouraged) flows, as observed in Seyfried et al. (2005) and Moussaid et al. (2016), respectively.

Seyfried et al. (2005) concluded that the relationship between density and velocity was governed by the properties of individual movements. For instance, the greater the density, the shorter the step length of each participant; hence, the linearly lower the velocity. This conclusion both concurs with and informs Weidmann's (1992) overarching findings for a single-file flow. Furthermore, the principle of a safety margin employed by each pedestrian is realised through a 'required length' (d m). This is described by Seyfried et al. (2005) as the length between a pedestrian and the next close-by pedestrian. The novel conclusion is that this safety margin varies linearly with velocity (v ms^{-1}) according to d = 0.36 + 1.06v. Pedestrian behaviour was found to optimise this distance, with high densities leading to 'lockstep' which optimises the limited space, shown in Figure 3.8.

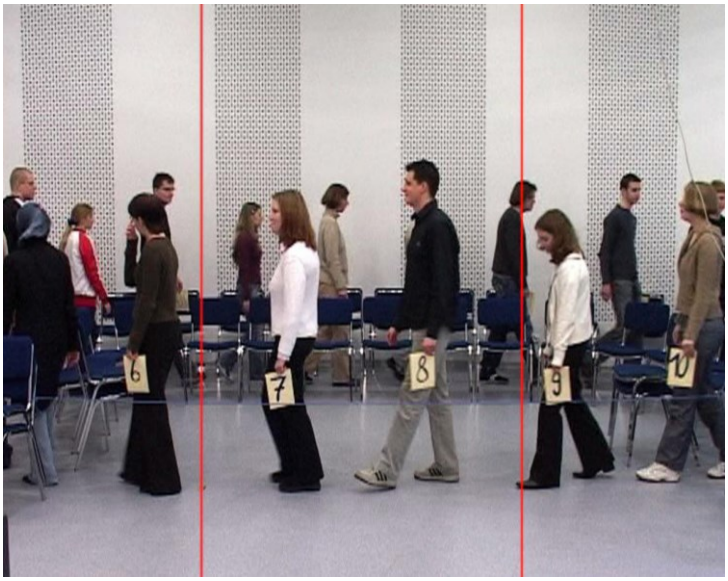


Figure 3.8: One frame of the standard video recording of the cycle with N = 20 after the preparation for the manual analysis (Seyfried et al., 2005).

Seyfried et al. (2005) confirms the need to observe individual behaviours in crowd flows (in simple unidirectional flows in this instance). Findings add to the hypothetical differences in behaviour that could be experienced by a visually impaired individual operating in such flows. Of most significance is how this pedestrian would regulate their safety margin. This is given the visual nature of this task, and whether such a relationship would remain linear or significantly different. Moreover, the use of mobility aids such as white canes can be inferred to interfere with optimising behaviours such as lockstep. Indeed, Seyfried et al.'s (2005) failing to test a heterogenous population is a limitation of this study that may have left several pedestrian behaviours undiscovered.

Schrater et al. (2000) and Hopkins et al. (2004) find that specialized neural mechanisms at the retina and brain-level are utilised by walking subjects to estimate the time to collision with surrounding obstacles. This is modelled by Moussaid et al. (2011) to be a critical component in determining unidirectional flow formations, including lanes, stop-and-go waves, collisions, and turbulence. These are especially prevalent in high densities and crowd disasters. Moussaid et al.'s (2011) model represents visual information through:

1. Current position and speed
2. Body mass
3. Comfortable walking speed
4. Destination point
5. Vision field of pedestrian (an angle to the left and right) and line of sight

Turano et al. (2004) and Subhi et al. (2017) explain that vision field is more complex than an angle representing vision width in the horizontal plane, as is inferred by Moussaid et al. (2011). The effects of vision field on walking speed are understood to be related to central or peripheral field loss. Additionally, Katemake et al. (2019) and Kumaran et al. (2017) find that line of sight and the ability to detect the final destination are correlated to visual acuity and contrast sensitivity, both of which are dependent on environmental lighting and contrast (Black et al., 1997).

Subsequently, it would be difficult to confidently input values into Moussaid et al.'s (2011) model in the context of crowds with visually impaired pedestrians. According to empirical modelling data referenced by Moussaid et al. (2011), as density increases, the flow changes from laminar to turbulent with the presence of stop-and-go waves increasing. Helbing et al. (2006) associates these with the amplification of small local perturbations in the flow as pedestrians fail to effectively coordinate their position when competing for scarce gaps. Assuming reduced vision field and line of sight, these coordination errors are likely to increase, leading to more stop-and-go-waves at lower densities. In extreme conditions, braking manoeuvres can result in backward moving waves (Moussaid et al., 2011).

This model therefore assumes that poorer vision would lead to poorer crowd efficiency at lower densities. Further research is therefore necessary to understand how the complex elements of visual function integrate into such models as the one proposed by Moussaid et al. (2011). More critically, these should investigate extreme conditions where adverse crowd performance could lead to jams and significant reductions in safety (Moussaid et al., 2011; Seyfried et al., 2009).

Seyfried et al. (2009) exemplifies this by investigating unidirectional flows of 20 to 60 pedestrians through bottlenecks of varying widths. 18 runs were captured through video recording, and experimental participants were instructed to travel through the section quickly but safely. A typical jam occurs when inflow exceeds the capacity of a junction; however, Seyfried et al. (2009) proved that crowd inefficiencies can cause jams at bottlenecks even if the capacity is not reached. Reasons for this occurrence are threefold. First is that local fluctuations in flow result in higher local densities that exceed local capacity. Second is the self-organisation of local groups of individuals that is dissimilar to the regular, global positioning, similarly leading to greater local density. Third is individuals' motivation to distance themselves from the person in front, as described by Seyfried et al. (2005) as a safety margin.

Interestingly, this third behaviour is found to depend on other pedestrians' ability to fill the gaps formed, agreeing with Helbing et al. (2006). Finally, in contradiction to the stepped manner proposed by Hoogendoorn & Daamen (2005), Seyfried et al. (2009) suggests a linear dependence between flow and bottleneck width. Notably, these behaviours occurred with a non-visually impaired experimental sample with reasons for jams that are likely to be exacerbated by a visually impaired population.

3.3.1.2. Opposing Flows

As with unidirectional flows, it is likely that opposing flows will form in large crowd flows. This is especially when considering complex environments with several accessways and bottlenecks including subway stations, public buildings, and ships (Helbing et al., 2002; Lozowicka, 2010). In addition, rapid changes in opposing flow dynamics can occur in high-stress operational scenarios such as evacuations when first responders are entering the evacuation zone (Lozowicka, 2010).

To demonstrate this, Helbing et al. (2002) employed a social force model of 200 non-visually impaired individuals where multiple behaviours were described. Helbing et al.'s (2002) observation of oscillatory changes between the alternating directions of motion supports the hypothesis that visually impaired individuals may experience unique forces in an opposing

flow, especially at bottlenecks. This phenomenon was most prevalent at doorways where, if one person moved through the gap, an individual behind them would follow easily through the bottleneck. However, as one side gained momentum, the opposing side had to come to a standstill. This is described by Figure 3.9, where the two differently shaded dots (light and dark) represent pedestrians moving in opposing directions of travel. In this scenario, the pedestrians represented by the lightly shaded dots gained momentum, thus obstructing the pedestrians represented by the darkly shaded dots.

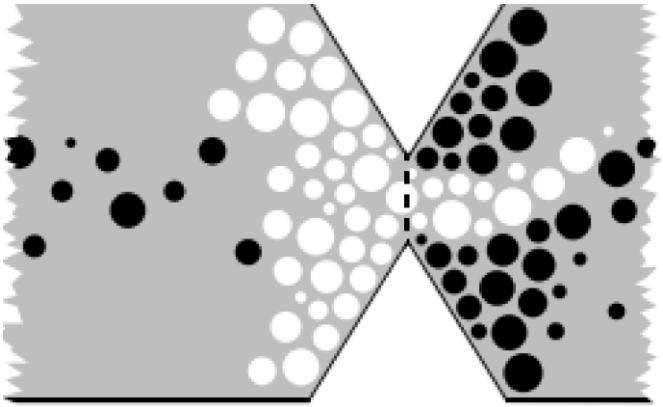


Figure 3.9: A deadlock occurring at a bottleneck where differently shaded spots represent pedestrians moving in opposing directions of travel (Helbing et al., 2002).

This scenario in an opposing flow compounds the behaviours that are expected to be unique to visually impaired individuals in individual, single-file, and unidirectional flows. These are: (1) visual coupling (Rio & Warren, 2014) in the initial following behaviour that leads to one side gaining momentum, (2) flow dynamics of the dominant side according to the zipper effect and layer headways (Hoogendoorn & Daamen, 2005), (3) magnitude of this momentum given mobility performance discrepancies between a homogenous and heterogenous population (Sharifi et al. (2016), (4) density effects in both sides of motion, including the presence of safety margins and self-optimisation such as lockstep (Seyfried et al., 2005).

Helbing et al. (2002) finds that, when people interact in an opposing flow, they continue to self-optimise to avoid collision by moving sideways in opposite directions. This leads to segregation, described as a lane formation. Its characteristics, including width and speed of formation, are dependent on the pathway width and density. Figure 3.10 describes a simple lane formation from an initially disordered opposing flow. As in Figure 3.9, the differently shaded dots represent pedestrians in opposing directions of motion. Lane formations in an opposing flow can therefore encompass several unidirectional flows with dynamic boundaries and flow widths.

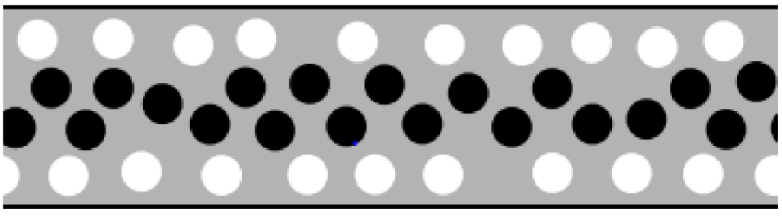


Figure 3.10: Lane formations in opposing flows where differently shaded spots represent pedestrians moving in opposing directions of travel (Helbing et al., 2002).

Experimental studies have been conducted to observe the behaviours of pedestrians in opposing flows. As with similar studies investigating unidirectional flows, testing populations remain generic with insufficient focus on visual impairment. Investigating these studies remains important as their findings allow for better estimation of expected performance. They form a baseline of comparison for crowds excluding and containing visually impaired members in experimentation conducted within this thesis.

Lee et al. (2003) conducted an experiment with 21 non-visually impaired pedestrians to observe the impact of an opposing flow on walking speeds under ship motion. A corridor 1.2 m in width was employed and the times for varying pedestrian configurations to travel 10 m along the corridor were measured. These configurations comprised movement as (1) an individual, (2) a unidirectional flow of 21 pedestrians, (3) an opposing of flow of two groups of 10 pedestrians, and (4) an opposing flow of one group of 10 pedestrians going against a single pedestrian. The time for 21 pedestrians to move through a doorway in single file was also observed.

A 20% reduction in walking speed was observed in (2) when compared to (1). In (3), pedestrians at the tail of both opposing groups showed lower average speeds relative to those at the head of the group. In (4), the single pedestrian showed a reduced speed relative to the opposing group, highlighting that opposing flows lead to a 30-60% reduction in walking speed relative to individual performance. Similar behavioural patterns were observed regardless of ship trim, heel, and motion, although overall reductions of 10-20% in walking speeds were recorded under dynamic ship effects. The effects of dynamic environments are therefore noted in opposing flows.

Lee et al. (2003) presents a simple, robust data collection methodology (8 video cameras along a straight corridor). However, the testing sample remains limited in that there was a younger, male-biased gender balance with exclusion of disabled participants. Uncertainty also exists as to how evacuation conditions were instilled on participants. These are all known to have an effect on an individual's walking characteristics (Chung & Wang, 2010; Boyce et al., 1999b; Moussaid et al., 2011).

However, Lee et al. (2003) presents an important practice in the testing of opposing flows, and this is the size and nature of each of the opposing groups. The position of the visually impaired individual within the group is therefore considered in experimentation within this thesis, where positioning at the head of the group appears to incur the greatest crowd-driven forces. This also includes scenarios where this individual is operating as part of a group versus group, or an individual versus group, in an opposing flow.

Findings from Lam et al. (2003) support this conclusion through the analysis of video footage of pedestrians at indoor walkways in shopping and commercial centres in Hong Kong. Opposing flows were observed to comprise major and minor streams, where a major stream contained a greater number of participants than the minor stream. Minor streams had more turbulent behaviours as individuals continually repositioned themselves when encountering and entering a major opposing stream. Consequently, pedestrians in the minor stream were more limited in choice as to how to avoid a collision. Lee et al. (2003) exemplified this when the individual pedestrian experienced the greater loss in performance upon encountering the group opposing flow. As did Helbing et al. (2002) when a bottleneck was dominated by the group that attained the greater momentum.

Moreover, Lam et al. (2003) suggests that the balance of the major and minor streams is one that could be optimised; the more similar the number of members of each flow, the more equally each stream shared the width of the walkway. Subsequently, for a given density, reductions in walking speed and pedestrian volume were at a minimum when the two streams had the same number of members. In agreement with Weidmann (1992), Lam et al. (2003) observed the effect of higher density in opposing flows to result in significantly fewer overtaking manoeuvres and a diminished ability of an individual to control their velocity.

As in Moussaid et al. (2010), the realistic operational scenario observed by Lam et al. (2003) enhances the likelihood of a heterogenous, and thus representative, testing sample. However, prior research by Lam et al. (1995) suggests that, while pedestrian characteristics were similar in Hong Kong to other Asian cities, these differed to pedestrian characteristics in Western cities. For instance, pedestrians in London and Calgary presented lower walking speeds under normal conditions, but vice versa under congested conditions.

Lam et al. (1995) is comprehensive in that several indoor and outdoor operational scenarios were observed, but incomplete as the pedestrian flows recorded were primarily unidirectional. Notwithstanding this shortcoming, study location should therefore be noted given regional differences in pedestrian characteristics. This may be exacerbated in the context of visually impaired mobility. Here, shifting cultural and regional attitudes to disability are shown to impose effects on both the disabled individual and the crowd's reaction to them (Bau, 1999).

3.3.2. Psychological Factors in Group Behaviour

Moussaid et al. (2011) observed differing behaviours in the directionality of the crowd through considering both a unidirectional and opposing motion. A novelty in the modelling approach used by Moussaid et al. (2011) to replicate these behaviours and validate their observations is the inclusion of cognitive heuristics:

> 'Understanding crowd dynamics through cognitive heuristics is therefore not only crucial for a better preparation of safe mass events. It also clears the way for a more realistic modelling of collective social behaviours, in particular of human crowds and biological swarms.'

While Moussaid et al. (2011) affirms the importance of psychological modelling in crowd behaviour, individual ability (including visual impairment) was not a consideration in their experimentation and modelling activities. Consequently, insufficient research exists as to how cognitive processes can affect visually impaired people in the unidirectional and opposing crowd formations described.

Therefore, a fundamental approach is suggested from classical psychology that is not specific to visual impairment. Self and social awareness are primary components of social behaviour, both in short-term group mobility scenarios and in long-term participation in society (Reicher, 2002). A comparison is drawn to the short-term and long-term cognitive state on the individual level. It is argued that self and social-awareness are the functions of the individual's cognitive state in the crowd, both in the short and long-term.

In considering long-term participation in society, for example, public self-awareness reflects an individual's concerns regarding how others evaluate them. This correlates with anti-

normative behaviours (Carver & Scheier, 1981; Fenigstein et al., 1975). Tuttle and Tuttle (1996) found feelings of withdrawal and depression in the development of a visually impaired individual. Stevelink et al. (2015) found similar feelings towards sight loss and mobility in semi-structured interviews with 30 visually impaired male ex-Service personnel aged under 55 years old. These where then found to drive such anti-normative behaviours.

Soon after becoming visually impaired, Stevelink et al. (2015) noted that personnel needed help and formed dependence on others. However, they experienced volatile strain in their relationships with family (designating new 'carer' roles) and withdrawal from broader social interaction. Stevelink et al. (2015) associated this with the self-awareness of embarrassment to ask for help, shame, frustration, and irritation. Moreover, personnel explained that coping mechanisms developed over time led to the evolution of these feelings into ones that are more positive. These included forming a better understanding of what they were and were not capable of, and thus goal setting and aspiring for self-improvement. Such includes self-acceptance and comfort in asking for help.

Indeed, human assistance (including sighted guides) and interdependence is therefore a critical aspect of visually impaired mobility and livelihood. Moreover, the nature of this human interdependence must be balanced, where external parties are educated, understanding, and empathetic of the visually impaired individual's physical and emotional wellbeing (Stevens, 2003). This is especially given the volatility of emotions that could be experienced by the visually impaired person. Such is why services as TfL's Turn Up And Go (TUAG) have become critical to some visually impaired transport users, where transport staff can provide advice, information, and assistance when travelling (Royal National Institute of Blind People, 2020a).

Stevelink et al. (2015) is limited in that all participants were male veterans serving in the armed forces. There is therefore uncertainty as to how these feelings would translate to a more heterogeneous visually impaired population. However, Stevelink et al. (2015) is useful in describing the effects of self-awareness on social relationships, and these are investigated in experimentation conducted within this thesis.

Indeed, dependence on others is shown to lead to pairing in crowds in Proulx (1995) in evacuations containing Persons with Reduced Mobility (PRM). Here, 62% of evacuees observed travelled in groups of two or three, including families. Groups slowed down and moved at the speed of the slowest person. In an extreme scenario, a PRM was unsettled, and their wheelchair blocked an exit, resulting in residents staying with her until firefighters arrived. This led to substantially reduced group performance as a result of the choices made by those residents.

Similarly, in the evacuation observed by Samoshin and Istratov (2014), visually impaired evacuees egressing as one large group segregated into smaller groups of three people in size. Moreover, individuals with greater impairment egressed quicker in a dense flow relative to a sparse flow. Therefore, while the presence of the visually impaired member could reduce the performance of a heterogenous crowd, the crowd could increase the functional performance of the visually impaired individual. This demonstrates that psychological factors could preside over physiological and widely-accepted relationships between density and velocity (Weidmann, 1992).

Likewise, in group evacuations of visually impaired people observed by Sorensen & Dederich (2015), individuals with better vision assisted those with worse vision. They sometimes returned to find others, causing opposing flows and leading to dangerous behaviour. Furthermore, some assistants made the other person to run. Interestingly, participants knew each other beforehand, although Sorensen & Dederich (2015) hypothesised that this was not a causal factor of these behaviour. Additionally, the visually impaired individual's fear of colliding with others, being a burden on others, and withdrawal from social interaction could further amplify such behaviours in crowds. Insufficient research exists to understand the extent to which these may occur, and are therefore of particular interest to the experimentation conducted in this thesis.

Secondly, the longer-term variation, development, and regression that can occur in the individual's self-awareness is considered. This is especially given the effect that this may have on their interaction with others. Stevelink et al. (2015), Tuttle and Tuttle (1996), and Bau (1999) explain that the psychological state of a visually impaired person does not follow a linear path. Instead, it can be unpredictable, especially in individuals that lose sight in later life in comparison to those that are born with no vision. Stevelink et al. (2015) summarises this through capturing a response from one of the personnel interviewed:

> 'Jack (combat-related visual impairment, 25–34 years): "It's been [years] now and there was a time I thought I'd accepted what had happened to me, but you know that was temporary. And yeah I don't think I've fully accepted what's happened to me. There [are] good periods and bad periods and you know they come and go quite randomly and yeah they affect me for different amounts of time and I can get quite negative sometimes and quite self-deprecating."'

Acting in conjunction to self-driven psychological variations are external factors in the operating environment. These include the crowd's social awareness that can lead to changes in the individual's self-awareness, producing anti-normative group behaviour. These operate interdependently in both the short and long-term, such as the immediate effects of social awareness in evacuation conditions, to the lasting changes in psychology permutating from the individual's family culture, respectively (Moussaid et al., 2016; Bau, 1999).

Short-term shifts in social awareness can permutate and drive the crowd's control over the individual. With enough shift in social awareness across several individuals through feedback loops and amplification, erratic physical changes in the crowd's structure and density can occur. Moussaid et al. (2016) demonstrates this in crowds undergoing evacuations with variable stress, conducting experimentation using an immersive virtual environment with human participants placed under controllable conditions. Stress is a psychological factor augmented through social awareness, such as individuals erratically acting upon the observation of other individuals fleeing an area. Moussaid et al. (2016) explains that stress can be manipulated by time pressures, a reward system, and environmental factors such as changing or flashing light levels.

Substantial differences in physical behaviour were observed as stress was varied by Moussaid et al. (2016). With minimal induced stress, participants remained safely spaced apart and collisions were at a minimum. Here, average crowd density was recorded at 2 persons/m^2. Under high-stress scenarios, herding and overcrowding were prevalent and crowd density

consequently increased to 5 persons/m^2. Helbing et al. (2007) shows that such a density results in crowd turbulence and substantial reduction in safety.

Shifting social awareness occurs in longer-term events and can sometimes do so unexpectedly. Such was observed during the Coronavirus-19 (COVID-19) pandemic caused by the new coronavirus SARS-CoV-2 (World Health Organisation, 2020). Including the physiological implications to human health, the pandemic spread panic and insecurity at all socio-political and economic levels (Zoumpourlis et al., 2020). The pandemic was linked to the onset of depression in many individuals due to the unprecedented and extremely restrictive measures that were implemented internationally. These included widespread mask-wearing mandates, social distancing (where individuals had to maintain a safe physical distance from one another to limit the spread of the disease), and stay-at-home orders.

Visually impaired people, as well as other vulnerable and older people (where visual impairment is most prevalent), experienced disproportionally greater impacts as they are at higher risk of infection or serious illness (National Health Service England, 2021; AgeUK, 2020]. AgeUK, the largest charity to support older people in the UK (and therefore a reliable representation of this population), described such sentiments as: ‘Covid has made me into a hermit afraid to go out and when I do I just want to get things done and get back home again to the safety of my home’, and ‘Being scared of contact with people and the isolation at same time’ (AgeUK, 2020).

Indeed, this represents negative self and social-awareness, and an ultimate regression in the individual’s psychological state. This affected both individual and crowd mobility. In a crowd, the visually impaired individual needed to maintain social distancing, and may have therefore experienced elevated and disproportional fear of collision with others. This is especially given a reduced capacity to detect the crowd. Contrarily, reliance on others to mobilise, such as a sighted guide, was more difficult to obtain given human health risks and social awareness of contact avoidance.

The criticality of meeting these needs was evidenced by the suspension of such services as TfL’s TUAG. This led to visually impaired organisations including the Royal National Institute of Blind People (RNIB) to campaign for confirmation on how blind and partially sighted people could be guided safely during social distancing (Royal National Institute of Blind People, 2020a). Moreover, this challenge has also been realised by emerging research such as Shrestha (2021) where a system was proposed for the active crowd analysis for pandemic risk mitigation for blind or visually impaired persons. Although, no crowd model or system has yet to receive widespread commercial adoption, therefore creating a research gap.

Finally, the longest-term factors on the psychological performance of a visually impaired individual in group behaviours stem from culture and long-term attitudes, as described in seven factors from Bau (1999). These encompass communication, health beliefs and practices, family structure, attitude toward authority, etiquette, expectations of "helping," and time orientation. These are supported by Spector (1996) and findings from the Minnesota Public Health Association Immigrant Health Task Force (1996) where recurring patterns in culture and diversity were observed in healthcare. They influenced when and how an individual would access healthcare and activities of daily living. Depending on culture, emphasis could be placed on the individual or on family, on independence or interdependence, and on competitive versus relational orientations.

The impact on mobility arising from such variation in culture and diversity remains largely anecdotal; Bau (1999) and Minnesota Public Health Association Immigrant Health Task Force (1996) suggest that O&M instructors and healthcare professionals should work with clients in a culturally-sensitive personal and professional basis to understand the individual's needs, performance, and outlook. This can include speaking the client's language, asking questions in a sensitive way, engaging their family, and forming partnerships in the community. Most importantly in the context of group mobility, it is further suggested that independence may not be the individual's ultimate goal. Bau (1999) exemplifies this through a realistic scenario where a woman relies on her family to mobilise:

> 'The O&M instructor first sets up an informal visit to the home of the elderly woman with the visual impairment to get to know the family and to discuss the woman's role and experience, past and present, in the family. The instructor observes the family's communication styles. She learns that the woman relies on her son, daughter in-law, and a grandchild to attend a local senior centre. After visiting the centre, the O&M instructor returns to talk further with the family, explaining and demonstrating O&M services. She suggests lessons for independent travel to the senior centre but determines goals with the entire family. Then, with family members welcome to tag along, she begins her assessment and training.' (p.296)

Hensen et al. (2017) conducted semi-structured interviews with eight visually impaired immigrants (seven females and one male) originating from Europe, Africa, the Middle East, South Asia, and South America residing in the Greater Toronto and Hamilton Area (GTHA). The cultural implications of visual impairment in the context of mobility and group interaction were most prominently described by female interviewees from the Middle East and South Asia, where visual impairment was discussed in terms of normalcy.

As similarly observed by Crabtree (2007) in attitudes towards disabled children in the United Arab Emirates, these participants described their disability as 'not normal' or 'damaged' within their culture, exacerbated by gender inequality. These negative cultural associations reflected in their daily life, preventing certain social relationships and the ability to interact with others. Moreover, Hensen et al. (2017) found inability to drive, affordability of transport, and weather and climate to all contribute to the individual's ability to socially integrate and, ultimately, mobilise.

In summary, a self-awareness of visual impairment can affect one's feelings towards themselves and others (Stevelink et al., 2015). In conjunction, others' social awareness of visual impairment can affect the group's attitude towards (and interaction with) the visually impaired individual (Hensen et al, 2017; Crabtree, 2007). These both operate in the short and long-term, from immediate shifts in group dynamics in evacuations (Sorensen & Dederich, 2015), to social distancing in pandemics (Zoumpourlis et al., 2020), to longer-term social exclusion driven by cultural stigma to disability (Hensen et al, 2017; Bau, 1999). Insufficient research exists to quantify how each affects the functional performance of a visually impaired person. Furthermore, self and socially driven attitudes towards seeking care, including O&M training that could improve social inclusion (Bau, 1999), are not rigorously understood. However, anecdotal evidence is available to qualitatively assess the psychological process of visual impairment and the cultural stigmas associated with this.

3.4. Summary of Findings and Introduction to the Research Challenge

It is found that several physiological and psychological factors impact mobility capacity. While effort was made to ensure that the mobility research observed was as empirical as possible, it remains difficult to compare across studies to conclusively state how each factor affects mobility. Several reasons exist for this.

Firstly, visual function (and other physiological factors) may only be indirect effectors on mobility capacity. Instead, psychological factors are responsible for determining mobility as the individual self-regulates according to their own intrinsic long-term psychological state. This coincides with their short-term state and knowledge depending on their operating environment and motivation (obstacle avoidance, wayfinding, and other tasks and subtasks). These motivations have yet to be rigorously defined and contextualised in existing research. Such also exemplifies the two-way relationship between capacity and performance, and the significant challenge of empirically determining mobility capacity while eliminating the effects of the environment and the user's motivations within it.

Secondly, empirical human modelling suggests a mesoscopic approach (thus requiring an understanding of individual and group behaviour). However, visually impaired individuals acting in a crowd hypothetically present the potential for significant, but unresearched, crowd perturbation and anti-normative behaviour. Fundamentally, this results from existing research strongly suggesting that normal crowd interaction requires a predominantly visual process, and that failure to effectively accomplish this could lead to collisions, turbulence, bottlenecks, and other dynamic crowd forces. This is further accentuated through the crowd's social awareness of the visually impaired person and the unpredictable behaviours that this may produce. This is exemplified as other pedestrians attempt to assist the individual while causing a disrupted or opposing flow.

Finally, and as explored in Section 3.5, each research study observed presents a broadly unique approach to its experimental methodology. While useful in obtaining a qualitative indication of each factor's influence on mobility, this greatly hinders fair comparability across studies. In turn, this limits the reliable, repetitive, and predictive quantification of each factor on mobility. This stems from inconsistent global and regional classifications of visual impairment, incomparable measures of participants' visual function and cognitive state (if even considered by the study), and varied mobility testing and outcome measures.

3.5. Methods and Shortcomings of the Current Understanding of Visually Impaired Mobility

3.5.1. Discussion on Assessing Individual Mobility

An inconsistent employment of mobility testing was found in the review of mobility capacity. Thus, a limitation is observed in understanding the most effective measure of individual mobility, and how this then compares across different visual impairments. Such remains true in research attempting to observe a similar dependant variable. Chang et al. (2020) conducted a systematic review of O&M outcome measures that investigated 32 individual studies, reaffirming that 'there are no gold standard measures or agreement on how to measure O&M performance'. The following were the methods of O&M outcomes observed, ordered from most to least prevalent within the review sample.

1. Efficiency (Time, distance, speed)

2. Obstacle contacts and avoidance
3. Disorientation and veering
4. Target identification
5. Safety and social interaction
6. Self-reported outcomes

Chang et al. (2020) further noted that these outcome measures of O&M were applied within different experimental scenarios within each individual study. These involved either controlled environments, real-world environments, or a combination of both. Chang et al. (2020) raised concern as to the comparison of a measure of O&M across studies, citing how such variations in experimental methodology can result in discrepancies.

For instance, the following articles use Preferred Walking Speed (PWS) and a calculated Percentage reduction in PWS (PPWS) to assess visual function and mobility. PWS can be defined as a 'baseline' walking speed where the visually impaired person travels at their optimum walking speed with the minimum mobility impact from their visual impairment Clark-Carter et al. (1986a). Hassan et al. (2002) tested 21 subjects with AMD and 11 normal subjects on a 20 m straight path (to obtain PWS) and a 79 m long and densely packed obstacle course (to obtain PPWS), finding only small variances in overall mobility between all subjects. The biggest decreases in walking speed occurred for those with increased binocular central scotoma (a loss of central vision).

Patel et al. (2006) tested a significantly larger sample of 1504 persons aged 72 to 92 across a 4 m straight path (to obtain PWS) and an obstacle course of undisclosed dimension (to obtain PPWS), finding visual field to be the primary factor in mobility. Comparatively, a study by Clark-Carter et al. (1987) tested only 3 subjects aged between 25 and 45 on an outdoor route. PWS was found by equipping the visually impaired test subject with a sighted guide, then eliminating the guide to find the reduction in PWS according to visual function. It was simply concluded that reduced visual function leads to reduced mobility.

A particular discrepancy between these studies is the inclusion or exclusion of a sighted guide in determining PWS; however, according to Soong et al. (2009) in observing 14 visually impaired subjects, no significant difference or superiority arises between each method. This was through calculating PWS by recording the time taken by each subject to walk an unobstructed, straight 20-metre corridor path with or without a sighted guide. Caution should be exercised in applying this finding to future mobility testing as the experimental sample had a relatively high mean age of 79.1 years old with a range of 55-89.

Additionally, discrepancies could result from differing testing environments even in studies with similar participant characteristics. Such is highlighted by further comparing the studies by Patel et al. (2006) and Hassan et al. (2002). Although the participants observed were of similar age, the values of PPWS observed within Hassan et al. (2002) were typically greater than those observed by Patel et al. (2006). This may have resulted from the obstacle course employed by Hassan et al. (2002), which was less complex than that used by Patel et al. (2006).

Indeed, while this example pertains to PPWS, it is noted that other measures such as target identification require a degree of intuition and subjectivity in their implementation. This was recognised as a limitation in Goodrich and Ludt (2003). The result of such exceedingly varying sample sizes, testing environments, and experimental methodologies leads to uncertainty in the

mobility capacity (and the resulting requirements) of visually impaired people. Indeed, in the prior comparison between Subhi et al. (2017) and Turano et al. (2004) on visual field, this may have driven the studies' opposing conclusions. Further complication also arose from variation in the O&M outcome measures employed by these studies.

Such remains true in medical research using mobility to assess the effectiveness of treatment for certain visual impairments. A case study is a comparison between the mobility testing protocols used by competing pharmaceutical organisations, Spark Therapeutics and MeiraGTx. Both are developing a treatment for RPE65 associated Leber Congenital Amaurosis, using mobility testing as a key indicator of changes in patients' visual capabilities (Rubin et al., 2010; Spark Therapeutics, 2019).

Spark Therapeutics conducts mobility testing using the Multi-Luminance Mobility Test Mat (MLMT), shown in Figure 3.11 (Spark Therapeutics, 2019). This mat comprises of symbols and instructions, directing the subject from a start point to an end point across the mat. The subject is first dark adapted for 40 minutes, allowing the eye to adjust to lower light intensities, and the test begins at the lowest tested luminance of 1 lx. The subject is then asked to traverse the map, following its instructions. Once complete, the test is repeated at a higher luminance. The luminance values tested are 1, 4, 10, 50, 125, 250 and 400 lux. A 'Pass' and 'Fail' threshold are then found at each light level for each eye tested, where a 'Pass' is defined as a pass with fewer than four errors and within three minutes (Spark Therapeutics, 2019).

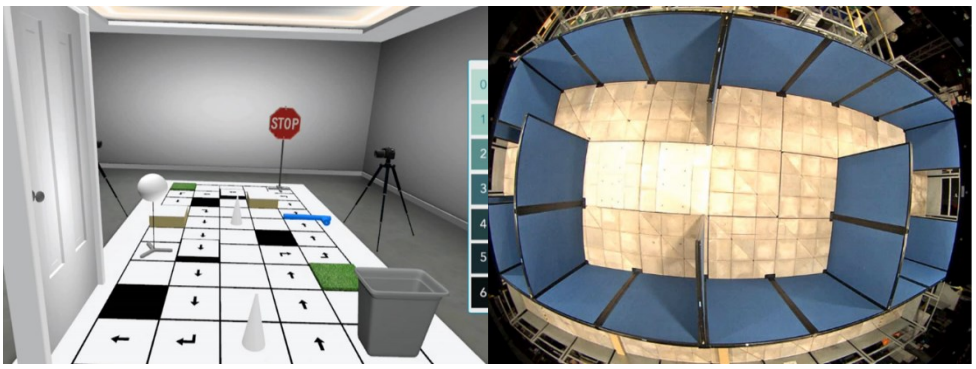


Figure 3.11: Spark Therapeutics MLMT (left) (Spark Therapeutics, 2019) and MeiraGTx PAMELA platform (right).

In contrast, the mobility testing used in the treatment developed by MeiraGTx takes place at the Pedestrian Accessibility Movement Environment Laboratory (PAMELA), a development by the Institute of Transport at UCL. This facilitates the study of a pedestrian's mobility under a variety of different controlled conditions. Here, patients are timed as they traverse a platform at decreasing luminance levels, taking note of any collisions or hesitations while walking.

The platform consists of three sections, a straight section to obtain baseline walking speed, a section with large barriers to simulate corridors (Figure 3.11), and a straight section with two foam blocks placed randomly apart to simulate smaller obstacle detection. The luminance levels tested are 256, 64, 16, 4, and 1 lux (Rubin et al., 2010; Kumaran et al., 2020). At each luminance level, the patient traverses the platform using one eye at a time, twice, leading to a total of four passes per luminance level. Patients are then given 10 minutes to adapt to the next lower luminance to be tested, and the test is repeated (Kumaran, 2018; Kumaran et al., 2020).

Very little similarity therefore exists between these two testing methodologies; the testing environments are incomparable, the light levels tested do not match and are tested in different orders, and the metrics collected to highlight changes in mobility are very different. Such is problematic as a comparable evidence base of mobility capacity fails to exist in applications where it is most critical. This is in determining the effectiveness of the only two competing medical treatments of their kind.

Such challenges extend to the observation of psychological and physiological behaviours pertaining to individual mobility. To overcome this, findings across studies are combined to create a holistic overview as exemplified in combining Brown et al. (1986) and Goodrich and Ludt (2003). Both studies investigated patients with ARM with very different testing methods and definitions of functional performance (Table 3.1). Brown et al. (1986) compared across patients and employed a comprehensive and qualitative assessment of visual function. Goodrich and Ludt (2003) observed the progression of each participant through their visual detection distance of different hazards following training and cognitive development. The conclusions obtained by both studies are complementary; Brown et al. (1986) allows for a 'snapshot' of the relationship between each visual function and mobility, while Goodrich and Ludt (2003) address long-term cognitive development within the individual that can influence functional performance.

However, this compilation of studies provides less opportunity for quantitative conclusions. A single, yet rigorous, study therefore remains more favourable. For instance, in Goodrich and Ludt (2003), only one measure was made per obstacle, and only three 'target' hazards were employed. This negated other differently sized obstacle (such as larger curb heights) that are likely to yield different visual detection distances. Had multiple measures including visual function tests been used, a better discretisation of the physiological/psychological factors would have been possible. In turn, this would provide greater understanding of the mobility needs of ARM patients in place of substituting Brown et al.'s (1986) findings to complete the analysis.

Notwithstanding this, reliability quantifying the effects of psychological factors remains challenging, more so than the currently available measures of visual function. Recognising these factors and employing systematic approaches to measuring them is therefore considered in this thesis' experimentation. Indeed, an ideal study incorporates quantitative mobility testing, as did Brown et al. (1986), with a longer-term observation of an individual's functional progression through quantitative data collection.

Self-reporting methods have become commonly employed in medical literature to address this, such as the physical function subscale in the Medical Outcomes Study Short Form-36 and the Physical Functioning Questionnaire in the National Health and Nutrition Examination Survey (Andrews, 2012). Andrews (2012) explains that such methods have shown favourable reliability and validity in determining patient's perceived difficulties with mobility. Such is why the revised CVI (2018) provides opportunities for the patient to report their own needs and functional performance, including living status, mobility difficulty, learning difficulty, employment, and education.

Furthermore, self-reporting has been widely applied to visually impaired-specific research in laboratory and real-world environments, such as in measuring fall rates and fear of falling (Szabo et al., 2010; Popescu et al., 2012), concern and anxiety in AMD patients (Taylor, 2019),

and road-crossing behaviours (Geruschat et al., 2006). Patient questionnaires and other methods of self-report are therefore considered to be an important tool in individual mobility testing.

3.5.2. Discussion on Assessing Group Mobility

In comparison to mobility research on individual capacity, there is significantly less available research on visually impaired crowd dynamics. Phenomena such as visual coupling, crowd forces, and social and self-awareness remain unexplored in the context of visual impairment. This is because existing research in crowd dynamics primarily incorporates a homogenous population of sighted pedestrians, often without mobility impairment (Daamen & Hoogendoorn, 2012; Gorrini et al., 2013; Rio & Warren, 2014).

Indeed, it is critical that research now explores the effects of heterogenous and impaired populations where these anti-normative behaviours can prevail. Indeed, such behaviour was observed in the evacuation monitored by Proulx (1995), where the reduced mobility of an individual also reduced the collective motion of the crowd. This was as 62% of evacuees within the crowd travelled in groups of 2-3, and each group slowed, in turn, to match the speed of the slowest person in the crowd. Likewise, Samoshin and Istratov (2014) observed that visually impaired evacuees egressing as one large group resulted in their separation into smaller groups of three people in size. Surprisingly, it was also found that individuals with greater impairment egressed quicker in a dense flow relative to a sparse flow, thus disagreeing with the widely accepted relationship between density and velocity in general group behaviour (Weidmann, 1992).

Shortcomings prevail in the limited, yet novel, experimentation that does consider visually impaired group mobility. This is exemplified by the study conducted by Sorensen and Dederich (2015) that investigated visually impaired evacuees operating individually and in groups. 40 participants aged 10-69 with a range of visual impairments were tested for horizontal walking speed and rate of descent on stairs. Tests were conducted to simulate evacuations in 2 and 3-storey buildings. This research could be considered the starting point for the investigation of previously unobserved phenomena occurring from the behaviour of visually impaired evacuees in groups. One notable conclusion was that, as sight reduces, the impact of crowd density on walking speed lessens.

However, this research was limited in that the data obtained was insufficiently controlled and repeated to allow for reliable use in empirical evacuation models. For instance, the environment tested was specific to this research, implying that the phenomena observed may not be reproduced in other conditions. Moreover, loud fire alarms were present which affected fundamental group interactions. Other factors such as familiarity with the environment, physical interactions between sighted and visually impaired evacuees, stress, and opposing flows were not controlled or considered.

Additionally, a limitation noted in the experiments conducted by Sorensen and Dederich (2015) is the data collection methodology used. This relied on the use of overhead video cameras, positioned at various angles given the confines of the evacuation environment being tested. This is illustrated in Figure 3.12.

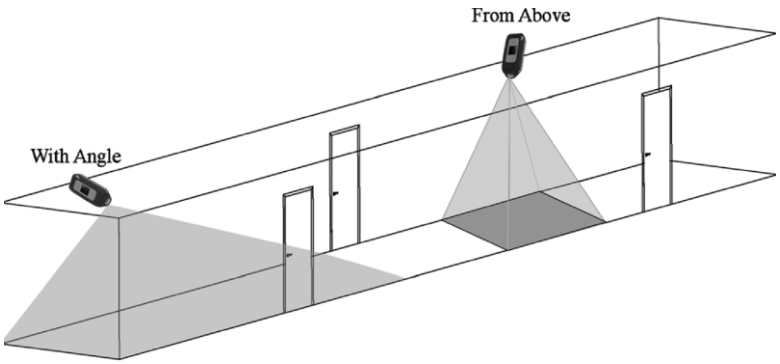


Figure 3.12: Limitation in recording area observed by Sorensen & Dederich (2015).

As can be seen, the behaviours of the participants were not captured by the recording equipment outside of the shaded area. Critical performance indicators and crowd interactions may therefore have been missed; especially as visually impaired people are more susceptible to rapid changes in performance when faced with changing obstacle densities. This was found by Zhang et al (2018), who observed how changes in obstacle density can impact the behaviour of eight normally sighted and 32 visually impaired pedestrians. Additional recording equipment is therefore considered within the experimentation in this thesis, including automated data collection systems such as Pozyx to capture the microscopic behaviours that may arise in group interactions.

3.5.3. Note on Experimental Design to Achieve a 'Real World' Capacity

It is concluded that rigorous function and functional measures are necessary for mobility capacity analysis. The more measures correctly captured, the more likely that patterns can be identified, and factors discretised. Such extends to the environment in which mobility research is conducted. As many elements should be controlled including, but not limited to, lighting, weather, and obstacles. Findings from the study by Leat and Lovie-Kitchin (2006) exemplify this and put forward recommendations on measuring mobility capacity.

To accomplish this, Leat and Lovie-Kitchin (2006) observed 35 participants on a multi-section mobility course. This is novel in that Leat and Lovie-Kitchin (2006) developed five sections of their experimental environment to exploit visual detection and identification distances, walking speed, and environmental errors. A small number of participants were used to iterate the testing environment until this was achieved, demonstrating a best-practice in testing environment design; exploratory testing of the experimental methodology with a small number of participants prior to conducting full-scale testing can return previously unknown design considerations. The following recommendations have been proposed by Leat and Lovie-Kitchin (2006). These are included as they provide an important background for the proceeding experimental research and analysis in Chapter 5:

1. Deliberately positioned obstacles may go astray and it is therefore recommended that natural obstacles be used as much as possible.
2. The mapping and positioning of obstacles should be done immediately prior to the subject undertaking the O&M task.
3. Obstacles used should allow participants to walk around them, thus reducing the participant's likelihood of moving them.

4. Safety can be enhanced through Leat and Lovie-Kitchin's (2006) use and positioning of real palm-like branches as it effectively mitigated the concern of participants injuring themselves.
5. Additionally, the use of paving imperfections and variation were safer obstacles than real steps; subjects made hesitations as expected in real-world performance, but without the risk of falling.
6. Other people working on or in close proximity to the testing course should be informed of the study and its undertakings to reduce the likelihood of external influence.
7. Increasing and varying the visual complexity of scenes more rigorously tests O&M skills and creates greater opportunity for errors. Visual complexity should therefore be considered, varied, or controlled according to the purpose of the respective study.
8. At least two experimenters should be present and involved throughout the experiment. This ensures sufficient attention and assistance can be given to participants, and that data collection capacity can be continuously maintained and rechecked
9. As was identified in Goodrich and Ludt (2003) when employing measures of visual detection distance or visual identification distance, participants should first undergo a 'training' session to familiarise themselves with the task's requirements.
10. To reliably determine visual detection distance, a very long pathway should be used with a distance of at least 29 metres, otherwise a 'floor effect' may be found for some subjects. A floor effect is characterised by a large proportion of participants yielding poor performance in the required task, thus skewing the results obtained and making differentiation between participants difficult (Šimkovic & Träuble, 2019).
11. Simple functional measures including walking times, hesitations, errors, and other behavioural modifications are useful and effective, as was likewise observed by Brown et al. (1986).
12. Instructions given to participants are critical in influencing their behaviour and these should therefore be scripted and controlled. For instance, if any contact is to be recorded as an error, then participants should be clearly informed that they should not touch objects.

Leat and Lovie-Kitchin (2006) connotes that subjectivity and intuition in mobility course implementation cannot be reasonably eliminated. For instance, an experimenter could void a participant's error if this was unforeseen in the instructions or an issue of interpretation. Contrarily, any collision or contact, including ones that would have been harmless in a real-world scenario, could be counted as an error if the instructions infer this. A consistent approach with clear instructions across a single study is therefore the most favourable approach.

Finally, limitations can prevail in experiments as rigorous in mobility course design as Leat and Lovie-Kitchin (2006). Here, experiments were conducted in daylight and thus shadows and illumination were not controlled or tested in photopic and scotopic settings. Moreover, data collection occurred manually rather than through video recording or more advanced automated date capture. For instance, the use of a laser range finder would have enhanced the accuracy and reliability of visual detection and identification distances. However, these limitations benefit the understanding on 'how' and 'what' can influence mobility capacity. This includes the way in which environments can be improved to test these. Proceeding research therefore builds on these testing methodologies through an iterative process.

3.5.4. Resulting Impacts on the Understanding and Modelling of Visually Impaired Mobility

Existing models of human behaviour are unlikely to reliably simulate visually impaired behaviours given poor availability of empirical data on their individual and group mobility. To investigate this hypothesis, the following table (Table 3.8) has been adapted from a review of evacuation models conducted by Kuligowski et al. (2010). The study was not specific to the modelling of visually impaired people by these models; rather, models were simply assessed on whether or not a function was present to represent those with any reductions to mobility.

Model	Disabled	Group	Opp. Flow	Fire	Toxicity	Pre-evac	Exit Block	Elevator	Route
EVACNET4	N	N	N	N	N	N	N	Y	Optimal routes
WAYOUT	N	N	N	N	N	Y	N	N	1 route, flows merge
STEPS	Y	Y	Y	Y	Y	Y	Y	Y	Conditional
PEDROUTE	Y	Y	N	N	N	Y	N	N	Shortest, optimal, signage
Simulex	Y	Y	Y	N	N	Y	Y	N	Shortest or altered distance map
GridFlow	Y	N	Y	N	Y	Y	Y	N	Shortest, random, user-def
FDS+EVAC	Y	N	Y	Y	Y	Y	Y	N	Optimal, conditional
Pathfinder 09	Y	Y	Y	N	N	Y	Y	N	Shortest, user-def
SimWalk	Y	Y	Y	N	N	Y	N	Y	Shortest
PEDFLOW	Y	Y	Y	Y	Y	Y	Y	Y	Shortest, conditional
PedGo	Y	Y	Y	Y	N	Y	Y	N	Probabilsitc/conditional, user-def
ASERI	Y	Y	Y	Y	Y	Y	Y	N	Shortest, user-def, conditional
BIdEXO	Y	Y	Y	Y	Y	Y	Y	N	Various
Legion	Y	Y	Y	Y	Y	Y	Y	Y	Conditional
SpaceSensor	N	N	N	N	N	N	Y	Y	Conditional – Visual perception
EPT	Y	Y	Y	Y	Y	Y	Y	Y	Shortest, conditional
Myriad II	Y	Y	Y	Y	Y	Y	Y	Y	Various
MassMotion	Y	Y	Y	Y	N	Y	Y	Y	Shortest, conditional
PathFinder	N	N	N	N	N	N	N	N	User's choice – 2 choices
ALLSAFE	N	Y	N	Y	N	Y	N	N	1-choice
CRISP	Y	Y	Y	Y	Y	Y	Y	N	Shortest, user-def, conditional
EGRESS 02	Y	Y	Y	Y	Y	Y	Y	N	Conditional
SGEM	Y	N	Y	N	N	Y	Y	Y	Shortest time, conditional
EXIT89	Y	N	Y	Y	Y	Y	Y	N	Shortest distance, user-def
MASSEgress	Y	Y	Y	N	N	Y	Y	N	Conditional – Visual perception
EvacuationNZ	Y	Y	N	Y	N	Y	Y	N	Various

Table 3.8: Review of evacuation models by Kuligowski et al. (2010).

Indeed, based on this review of egress models by Kuligowski et al. (2010), it was found that 21 out of the 26 models reviewed allowed for the inclusion of the egress capacities of disabled people. Moreover, 19 out of the 21 models considering disabled evacuees also consider an opposing flow. It therefore appears that the majority of egress models do indeed attempt to include disabled evacuees and their behaviour in sub-optimal pedestrian flows. However, as hypothesised, the primary shortcoming of current models is their fundamental implementation of the disabled user and the insufficient realism of the crowd simulated around them. This is reaffirmed by (Christensen & Sasaki, 2008):

> 'Current evacuation models either do not address individuals with disabilities in their simulated populations, or simulate a 'standard' individual with disabilities by generally limiting their speed of movement, an approach which does not represent the disabled population.'

Christensen and Sasaki (2008) propose new modelling principles in the development of their BUMMPEE agent-based evacuation model, aiming to better incorporate people with reduced mobility. For the individual, Christensen and Sasaki (2008) propose modelling parameters including speed, size, ability to navigate terrain, perception (visual, hearing), psychological profile (confidence, stability), and their need for assistance (including sighted guides, manual or automatic wheelchairs). Moreover, inclusion of four environmental factors is considered:

1. Exit Character – Stepped landings, high doorways, and other exit methods may act as a barrier for disabled individuals, such as for wheelchair users attempting to navigate revolving doors.
2. Route Character – Paving material, sloped walkways, stairs, high glare surfaces, and other route characteristics can impede the passage of disabled individuals.
3. Obstacle Character – Street furniture, vehicles, moving walkways, and other static and dynamic obstacles may act as barriers or impact the egress speed of a disabled individual.
4. Planned Systems – refuge points, evacuation elevators, stairwells, and other systems designed to assist an individual, especially one with a disability, in an evacuation.

In addition, Christensen and Sasaki (2008) propagate a shared, rather than individual, knowledge model, with benefits including less computation and greater realism. Indeed, it is evident that several aspects of mobility capacity are considered by this modelling approach, although visual impairment is only one of the disabilities featured within BUMMPEE. Such positive developments include the modelling of perception (visual function) and psychological factors within the agent, and the modelling of glare and other environmental factors on the agent's mobility.

However, there remains uncertainty as to how this model includes other factors known to affect mobility capacity, including complex visual function (such as the nature of visual field loss), knowledge, cognitive state, and crowd behaviour. Crowd behaviour, in particular, is not detailed in BUMMPEE's modelling approach. To address this, an extended BUMMPEE model was developed and analysed by Koo et al. (2013). It was then tested against an evacuation of a heterogenous population in a building. 14% of the population had a disability of which 1.5% were visually impaired. The simulation was analysed under two controlled evacuations, one evacuation depended on the agent's impairment and the other depended on the agent's location within the building.

Utilising maximum walking speeds obtained from other studies, the following was set in the extended BUMMPEE model; for agents without a disability, walking speeds horizontally, on stairs, and when negotiating an obstacle were 1.25 m/s, 0.70 m/s, and 0.70 m/s, respectively (Boyce at al., 1999b). For a visually impaired agent, walking speeds horizontally and on stairs was 0.86 m/s and 0.61 m/s, respectively (Wright et al., 1999). A speed when negotiating an obstacle was not defined, demonstrating a limitation in practical implementation of this model for visually impaired mobility. The use of only maximum walking speeds without variability is a further shortcoming. Further data collection is therefore necessary to understand BUMMPEE's potential, especially for visually impaired individuals.

It is argued that, where walking speeds are provided, it would be difficult for models attempting to recreate these to understand how or why these speeds were obtained. In the evacuation

conducted by Sorensen & Dederich (2015), horizontal walking speeds of the 40 visually impaired evacuees were found to be between 1.19 m/s and 1.34 m/s, presenting up to a 56% (2 s.f.) difference from the speed of 0.86 m/s referenced in Koo et al. (2013). Additionally, this performance was obtained through participants using their environment such as holding onto walls when egressing and being in physical contact with obstacles to register them.

Walking speed, while being a primary modelling output, is therefore not solely sufficient to describe the performance of a heterogenous population; Sorensen and Dederich (2014) tested the performance of the STEPS (version 5.1) agent-based microsimulation tool for heterogenous and homogenous crowd simulation, comparing the simulation to an experimental evacuation of a train in a tunnel. This builds upon findings from Kuligowski et al. (2010) and Campanella et al. (2009), where it was concluded that an increase in the population's heterogeneity has wide-spread impacts on evacuee performance, reducing speed, densities, and flow stability.

Sorensen & Dederich (2014) found that the heterogenous group (including older people, people with mobility, visual, auditory, and cognitive impairments, and people without a disability) had an evacuation time double that of the reference homogenous group without a disability. Moreover, whilst STEPS did not yield conservative estimates, it performed better for the homogenous groups. The model also failed to account for specific human behaviours. For instance, overtaking was rarely observed in the heterogenous group, but did occur in the simulation.

Furthermore, the model did not demonstrate the assistance to the disabled evacuees provided by the able, the queuing observed by hearing impaired evacuees, and the bottlenecks caused by mobility impaired evacuees. Therefore, the good prediction of egress time by STEPS is useful, but only to an extent as it does not sufficiently reproduce heterogenous human behaviour that could impact safety.

A model that is not specific to visual impairment can still include sensory modelling parameters that are relevant to a visually impaired individual. This is the Smoke Effect and Blind Evacuation Strategy (SEBES) module created by Nguyen et al. (2013), an agent-based model that attempts to simulate low-visibility environments resulting from smoke during fire evacuations. The concept of this model builds on fire experts' advice on smoke, its visibility, and inhalation effects, including that evacuees follow walls and obstacle boundries until an exit is reached.

The modelling agents are therefore the evacuee, an alarm, fire, smoke, and signage and plan (a fixed variable). A 'blind movement' principle is proposed where, as smoke increases, sight and visibility decreases. At high visibility, evacuees are modelled to follow evacuation signage, the crowd (visual coupling), and their own route (plan). At low ('blind') visibility, evacuees are modelled to follow walls and move more randomly.

Indeed, these movements agree with a real evacuation of visually impaired people conducted by Sorensen and Dederich (2015), which includes the most severely visually impaired people following walls and obstacle boundaries. However, it is noted that models incorporating externally driven sensory impairment, as does SEBES, are unsuitable for modelling visually impaired individuals. This is as they negate the complex tacit knowledge and cognitive ability possessed by a biologically visually impaired individual (Passini et al., 1990). Further limitations include an assumption of immediate blindness (without varied visual function) in

smoke. Moreover, age, location, and other randomised movements not caused by smoke are excluded.

In summary, there appears to be strong preference for agent-based models in simulating unique human behaviours. This is intuitive given that physiological and psychological behaviours stem from the individual (the agent at the microscopic level), their motivation, and their interaction with the environment. This then propagates to the crowd (macroscopic level) to form the desired mesoscopic approach. Models such as PEDFLOW, BUMMPEE, and the SEBES module are commendable in that they continually add to the agent's controllable parameters, allowing for input of these physiological and psychological factors that was previously not possible.

In application, however, limitations remain. It is evident that models have yet to consider the parameters that are proposed in advanced medical and engineering literature, including visual function, tacit knowledge, and a visually impaired person's unique short and long-term cognitive state. These shortcomings are difficult to rectify given insufficient quantitative mesoscopic data for which these models can be validated against. This extends to empirical information on disabled people's behaviours during emergency evacuations (Christensen & Sasaki, 2008).

Consequently, expert advice, anecdotal data, and intuition prevail in many developing models including BUMMPEE and the SEBES module. The result is modelling that appears reasonable, but fails to identify certain significant behaviours; Christensen and Sasaki (2008) realise that the BUMMPEE model may not be internally accurate even when the results appear to be reasonable, and Sorensen and Dederich (2014) find that STEPS provides realistic egress times but fails to recreate many of the safety-dependant behaviours in a heterogenous population from a real evacuation. Model shortcomings are compounded by failing to consider the time to start evacuating, not differentiating individual start locations and their interaction with the environment (which affects exit choice), and assuming that the individual travels at their maximum speed. Therefore, an optimistic simulated mobility is typically yielded (Christensen & Sasaki, 2008).

3.6. Conclusions from the Literature Review and Innovations in the Proposed Research

The study of human crowds is a complex and interdisciplinary field, this is as microscopic individual-level behaviours can have macroscopic impacts on the behaviour of the crowd. It is therefore important to obtain an extensive understanding of individual mobility, especially in the context of visual impairment and disability where uncommon mobility characteristics may prevail.

Mobility capacity is found to include physiological and psychological factors, both in individual and group operation. Each factor is explored in depth, and a holistic understanding of its effect on capacity is obtained. However, mobility data for the visually impaired population is often incomparable, and therefore unsuitable for use in the prediction of group behaviour. This is especially true given the varying testing protocols utilised within medical and engineering research. These findings extend to research involving group mobility and evacuation monitoring. Ultimately, human behaviour modelling relying on experimental data therefore fails to accurately represent disabled and visually impaired people.

This research therefore proposes and conducts experimentation in Chapter 4 and 5. This aims to depict individual mobility across different visual impairments, and its translation to group performance under multiple empirical scenarios and flow types. A novel testing methodology is defined, iterating on currently accepted experimental methods while addressing shortcomings. The data collected in this thesis is therefore used to deliver a better understanding of mobility capacity and its variation in an empirical environment. Following this, further work proceeds into contextualising these findings under different environments and mobility augmentations.

4. Methodology for Addressing Shortcomings in the Understanding of Mobility Capacity and Assessment of Mobility Performance

Chapter 2 finds that mobility performance and user requirements are effectively derived following an understanding of mobility capacity. However, a critical literature gap identified in chapter 3 is insufficient data availability for visually impaired people operating in crowds, an important component of mobility capacity. This chapter details the methodology employed to address these findings, and to meet the aims and objectives of this thesis moving forward. Section 4.1 overviews this multi-phased methodology, and proceeding sections detail the individual phases within it.

4.1. Methodology Overview: Three-Phase Approach

As several factors affecting the mobility of the visually impaired exist, such as the significantly varied impacts on sight caused by different visual impairments, the research must consider a controlled approach to data collection, analysis, and requirements derivation. The research must also remain focused and within scope. Subsequently, a methodology with three phases is defined, as follows:

1. Creation of an empirical experimental methodology:
   Following identification of shortcomings in the understanding of mobility capacity, a data collection and analysis methodology is developed to address these.
2. Execution of the empirical experimental methodology:
   Execution following development of the data collection and analysis methodology.
3. Assessment of mobility performance and development of new requirements:
   In considering novel findings in mobility capacity and its measurement, a review of mobility performance proceeds. Further experimentation is conducted if discrepancies or shortcomings are observed.

4.2. Phase 1: Creation of an Empirical Experimental Methodology

The literature review finds that current models cannot reliably reflect the behaviour of visually impaired people, individually and in crowds. This is a result of insufficient data on the mobility capacity of visually impaired people, especially in crowds. Isolating the effects of one causal factor is difficult given the multitude of factors and their interlinked nature. Moreover, the differently applied classifications of visual impairment limit comparability in the research that is available. An experimental methodology is therefore developed to produce this data, and it is carefully controlled in the environments and scenarios that it incorporates.

The methodology aims to assess how the visually impaired individual behaves in controlled, empirical environments. Individual mobility is first tested in each environment, and then compared to mobility in a multitude of crowd flows. The literature review finds that restricted and unrestricted unidirectional and opposing crowd flows present a wide set of crowd scenarios. Mobility outcome measures feature quantitative and qualitative methods to maximise data capture. These include walking time, effective speed, actual speed, orientation errors, and path inefficiencies. In addition is the use of questionnaires prior to and following

experimentation to ascertain visual function and the participant's self-reported sentiment throughout the experiments. Figure 4.1 represents the principal stages of this phase.

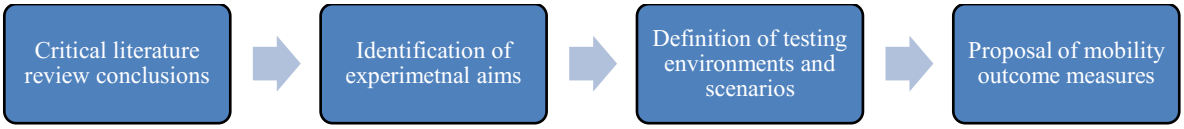


Figure 4.1: Principal stages of Phase 1.

4.3. Phase 2: Execution of the Empirical Experimental Methodology

Following the creation of the methodology, its execution then proceeds. This involves preliminary logistics and ethical approval, construction of the empirical environment, the setup of data collection equipment, participant recruitment, and trial runs. Following execution, a substantial volume of data is collected from the experiment including questionnaires, video footage, and automated positioning data. Data labelling, cleaning, and analysis proceeds. The result is new mobility data on visually impaired people operating individually and in crowds in different empirical environments. These are finally contrasted to findings from the literature review to identify disparities. This phase is graphically represented in Figure 4.2.

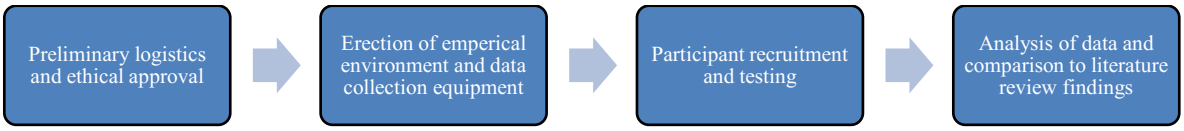


Figure 4.2: Principal stages of Phase 2.

4.4. Phase 3: Assessment of Mobility Performance and Development of New Requirements

Upon completion of the data analysis, an enhanced understanding of mobility capacity is obtained. A critical review of the current understanding of mobility performance can then proceed considering environmental and technological augmentations. Areas in which the underlying human factors have not been effectively considered are highlighted. Following this, all findings are consolidated in the framework of requirements for visually impaired mobility. Further experimentation is designed and conducted to validate these requirements in the design of a navigation system for visually impaired people. In addition, semi-structured interviews and thematic analysis are executed with visually impaired participants to identify challenges in environments not found in the literature review. The fundamental research aim is therefore realised and validated through practical implementation. This phase is graphically represented in Figure 4.3.

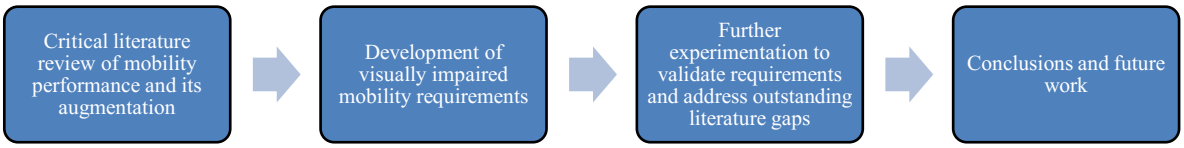


Figure 4.3: Principal stages of Phase 3.

5. Investigating and Comparing the Behaviour of Visually Impaired People in Unidirectional and Opposing Crowd Flows

This chapter describes and executes experimentation to address the literature gaps identified in Chapter 3 according to the methodology proposed in Chapter 4. These include the unavailability of behavioural data for visually impaired people in crowds, and the need for an empirical and consistent experimental process to overcome this. Section 5.1 introduces the testing environment and its integrated data capture systems. Section 5.2 elaborates on the testing scenarios, while sections 5.3 and 5.4 introduce and detail the participant sample, respectively. Sections 5.5, 5.6, and 5.7 discuss the results from the individual, unidirectional, and opposing flow scenarios, respectively. Section 5.8 summarises these results, and section 5.9 presents findings from variations in the experiment. Section 5.10 concludes this chapter with key results and limitations. A significant volume of data is collected and organised through this experiment. This is included across Appendices D to M and used throughout the chapter. Table 5.1 describes the relevant appendix structure for ease of reference.

Appendix	Contents
A	Script Verbally Delivered to Brief and Debrief Participants
B	VIP Questionnaire
C	NSP Questionnaire
D	VIP and NSP Additional Preliminary Information
E	VIP and NSP Individual (Baseline) Results
F	VIP in Unidirectional Crowd Flow Results
G	VIP in Opposing Crowd Flow Results
H	Results for Variation in Experiment (Session H, I, and J)
I	VIP Post-Experiment Questionnaire Results
J	NSP Post-Experiment Questionnaire Results
K	Session J (Additional NSP Opposing Group Flow) Questionnaire Results
L	Pozyx Data Extraction Code (MATLAB)
M	Methodology of the Hypothesis Testing

Table 5.1: Overview of Appendices Relevant to this Chapter.

5.1. PAMELA and Mobility Course Configuration

5.1.1. Introduction to PAMELA

Prior to developing new mobility frameworks, an experiment to observe the behaviour of visually impaired users in a controlled series of environments, under unidirectional and opposing crowd flows is proposed. The outcome of this experiment is to provide an empirical model that can predict the movement of visually impaired people with different visual impairments in a wide range of normal and evacuation scenarios in various environments, as individuals and in crowds. The outputs of this testing can then be refined and built upon by further research within the thesis, extending to the augmentation of environmental features to the use of indoor navigation systems.

The Pedestrian Accessibility Movement Environment Laboratory (PAMELA), a development by the Institute of Transport at UCL, can facilitate the study of a pedestrian's mobility and their interaction with the immediate environment under a variety of controlled conditions. The facility is located in Tufnell Park, London, and centrepieces a computer-controlled

configurable platform comprising 60 square modules, 1.2 m in length and width, with interchangeable surfaces, giving a total surface area of approximately 86 m^2. Modules can be manipulated to present steps, gaps, and longitudinal and cross slopes of up to 20% (Boampong et al., 2015).

Variable lighting and dynamic ambisonic sound systems are present, but only the variable lighting system is relevant to this study as no additional aural stimulation through the facility's sound system was employed. 44 solid state LEDs combine to produce PAMELA's variable lighting system, each with capacity to change intensity and colour saturation independently. The platform surface's illumination can be varied from near darkness to over 1,000 lux is possible. Lighting temperature can be varied from warm to cool, and colours can be blended by mixing red, green, and blue (Boampong et al., 2015).

PAMELA therefore provides the ideal facilities for the construction of an empirical environment. This is critical for this experimentation which aims to isolate the effects of different group scenarios. Subsequently, as many factors as possible must be controlled beyond the influence of these scenarios. Here, an environment can be constructed to exacting specification, and tested over a period of time without variations in lighting, auditory references, walking surfaces, weather conditions, and other external factors. Every participant observed will therefore operate through an identical mobility course.

5.1.2. Platform and Mobility Course Configuration

A mobility course with definable sections and obstacles was erected on the platform at PAMELA to create a mobility course. Participants were then asked to traverse this mobility course on the platform through a predefined route under different testing scenarios. The platform layout is similar to that used in the OPTIRPE65 MeiraGTx clinical trial and has been validated to be empirical, repeatable, and relevant to real-world visually impaired performance (Kumaran, 2018; Kumaran et al., 2020). This environment has yet to be used with a broad range of visual impairments under individual or group motion, and this experiment is therefore a novel application of a novel mobility course. As shown by Figure 5.1, three discrete sections of the platform were defined as follows:

1. A straight section to obtain a baseline for the participant's typical walking speed.
2. A 'maze' with barriers a participant must navigate through to recreate passageways.
3. A straight section with 2 foam blocks spaced randomly apart and on either side of the walking path to simulate smaller obstacles and steps.

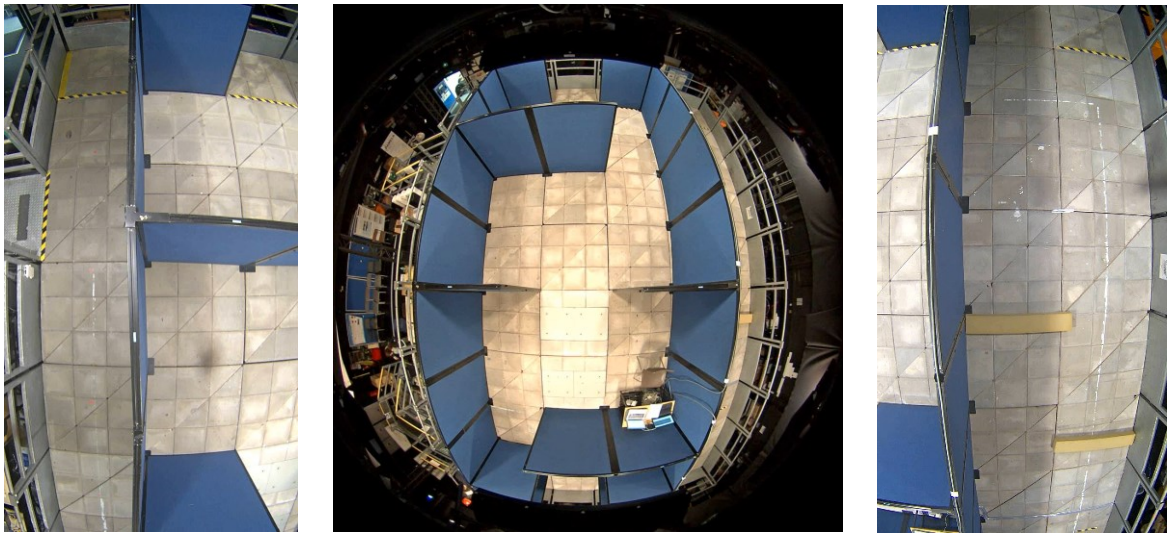


Figure 5.1: Section 1 (left), section 2 (middle), and section 3 (right) of the platform erected at PAMELA.

The modular walls erected to section the platform and create the maze are 1.2 m in length and 1.8 m in height. They are affixed to the edge of each square module when needed and have a narrow black border running around a navy-blue fabric façade. While the walls can be reassembled and moved, they do not move under the collision force of an experimental participant and thus present a fixed obstacle. All modular walls remained in place throughout the experiment and were not moved.

The chair, desk, and laptop positioned in the corner of the maze were necessary for the control of the Codamotion system given operating range constraints. Collectively and with the seated experimenter, they occupied a square of length 0.4 m and were tightly positioned in the corner of the two adjacent walls. No other wiring or unintentional obstacles were present across the platform. While these items were placed as far from the walking path as possible, there remains a potential for their interference with crowd flows during high densities as they occupied walkable space within the maze.

The foam blocks are 1.2 m in length, 0.2 m in depth, and 0.13 m in height. Their colour is a light yellow with chromaticity coordinates (0.46, 0.42) and a Weber contrast of 0.32 relative to the platform floor (Kumaran et al., 2020). They are placed across section 3 and at its approximate centre, requiring participants to either step over or walk around them. They are not fixed in place and can be moved by participants in a collision. The platform layout can be observed in Figure 5.2, including a representation of the most effective walking path across each section.

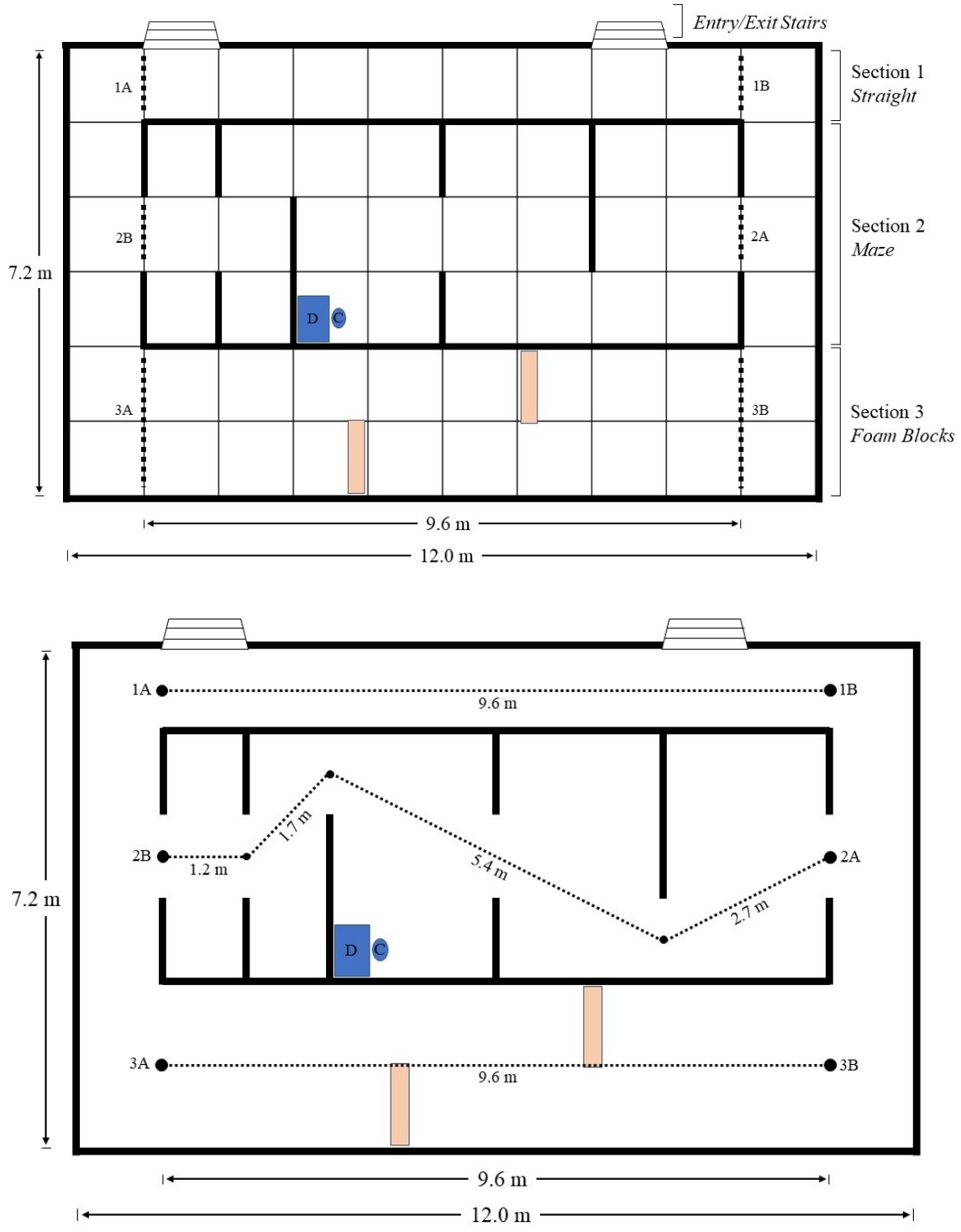


Figure 5.2: Mobility course configuration and walking path on the platform at PAMELA.

The gridlines represent each square module of length 1.2 m on the platform floor. In the experiment, the edges at which modules meet one another present insignificant visibility or tactility to participants. The platform's walking surface can therefore be considered to be hard, flat, and homogenous throughout. The stairs marked above section 1 were solely used to enter and exit the platform and were not part of any mobility testing. Moreover, their positioning at the edge of the walking path with sufficient walking space barriers around them mitigates their interference with participants during the experiment.

The desk (D) and chair (C) are marked on the figure. The thickest black lines around section 2 represent the positions of the walls as configured throughout the entirety of the experiment. The thickest black lines around the perimeter of the entire course are permanent metal barriers to prevent participants from falling off the platform. Including the configured walls, Figure 5.1 pictures the permanent metal barriers which featured a solid plate at floor level. Canes or other mobility aids would therefore not slip below any of the walls or barriers utilised within the experiment.

The dotted lines represent the points at which the participants would start and stop at each section, and these were marked by yellow and black striped tape on the ground. At the start of each section, participants were positioned behind the start line and were given a verbal 'go' instruction to proceed. They were instructed to stop and wait at the end of each section, and were then positioned to traverse the next section. While data capture was continuous, only data for when the participant crossed the start and stop line for each section was filtered and analysed post-experiment. Therefore, while a significant volume of data was collected, this approach ensured that start and stop events were captured and controlled, both spatially and temporally.

Forward and reverse passes of each section were conducted. A 'forward' pass for Section 'X' represents movement from 'XA' to 'XB'. For instance, a forward pass for Section 2 starts from 2A and ends at 2B. A 'reverse' pass for Section 'X' represents movement from 'XB' to 'XA'. For instance, a reverse pass for Section 2 starts from 2B and ends at 2A. Participants completed forward passes first, moving from 1A to 1B, 2A to 2B, and then 3A to 3B, then completing reverse passes from 3B to 3A, 2B to 2A, and 1B to 1A. Figure 5.2 illustrates the shortest and most efficient walking paths for each section. Distances have been calculated to a precision of 1 decimal place:

1. 1A to 1B = 1B to 1A = 9.6 m
2. 2A to 2B = 2B to 2A = 11.0 m
3. 3A to 3B = 3B to 3A = 9.6 m

Lighting was calibrated and fixed to present a uniform illumination of 256 lux at platform level throughout the entire experiment. This aimed to control the impact of illumination on mobility while simulating typical indoor lighting as found in an office or shop. Indeed, a compromise was necessary as too little illumination would have limited visual function and environmental perception in some participants, while higher values may have caused disability glare in others. Natural lighting was not present at the platform. No additional audio systems or artificial auditory reference points were used throughout experimentation apart from verbal instructions presented prior to and following each pass. The facility was set at room temperature with no notable wind on the platform.

5.1.3. Data Capture and Equipment

Manual and automatic data capture solutions were implemented to allow for cross-comparability, backup, and validation of collected data. Cameras were present and aligned over each section of the platform. These recorded all aspects of the experiment. Section 1 and 3 each had two cameras spaced along the walking path while section 2 had a single camera positioned above the maze. In conjunction, the cameras allowed for complete visibility of the platform surface, including every section's start and stop markings.

Pozyx, a software/hardware Real-time Locating System (RTLS), was implemented to support the data captured from video recordings and was used to track all participants in all sections. Participants wore helmets with Pozyx tags affixed to them while five Pozyx anchors were positioned and calibrated around the platform (four on the ceiling at each corner of the platform and one at floor level on the sidewall of section 1).

Moreover, the Codamotion positioning system was used to track the movement of up to two visually impaired participants in section 2, allowing for a separate data fusion study to take place outside the scope of this research (tracking of other participants through other sections was unfeasible given data accuracy and equipment constraints). The Codamotion camera was positioned directly over section 2 and two helmets included both a Codamotion and Pozyx tag. These were clearly numbered with reflective tape to distinguish between VIP 1 and VIP 2. Codamotion data was not analysed as part of this research.

All helmets were fluorescent orange and, excluding the two helmets with reflective tape to identify the visually impaired participants, featured no other markings. As a result, participants were clearly and equally distinguishable regardless of position or velocity on the platform. While video footage was used as the primary data source given high reliability and coverage, data collected from Pozyx and Codamotion was cross-compared to support findings and identify exact and precise movements. Useful automatic data captured through Pozyx included the tagId, connection status, timestamp, an error code (if present), data metrics and debugging (latency and anchor status), 3D tag position, 3D tag acceleration, and each tag's accelerometer reading. Data was refreshed and recorded ten times per second. Finally, in addition to data collection equipment present on the platform, participants were presented with questionnaires prior to and following the experiment. These are described in section 5.3 where the procedures when working with participants are detailed.

5.2. Testing Scenarios

5.2.1. Overview of Scenarios

Five different testing scenarios were defined according to the fundamental variations in crowd flows observed throughout the literature (Seyfried et al., 2005; Seyfried et al., 2009; Helbing et al., 2002; Lozowicka, 2010):

1. Individual
2. Unidirectional Group Flow – Restricted
3. Unidirectional Group Flow – Unrestricted
4. Opposing Group Flow – Restricted
5. Opposing Group Flow – Unrestricted

The 'individual' testing scenario comprised of one forward pass and one reverse pass per participant, thus yielding two traversals for each section and providing an additional result for comparison. All other scenarios included one pass of each section for each participant. It was assumed that this was sufficient to extract crowd behaviours as these are short-term, spontaneous events (Helbing et al., 2002). Results from the initial passes are therefore likely to be the most representative of real-world behaviour.

A 'restricted' case and 'unrestricted' case were stipulated. Participants were advised to traverse the platform as quickly as possible in both cases. In the restricted case, participants were told

to traverse the platform whilst adhering to the speed of the slowest person in the group. This was intended to maintain group cohesion. In the unrestricted case, participants were instructed to traverse the platform freely, overtaking if desired, without jogging or running. The unrestricted scenario aimed to induce higher stress and more dynamic behaviours than its restricted counterpart. The order in which the unrestricted or restricted instruction was given at the start of each section of the platform was randomised. However, it was ensured that each section underwent one of each type of pass.

On completion of the data collection, the following are found for participants in each scenario:

- Time to traverse each section from the video footage (confirmed by Pozyx data)
- Effective speed from the time to traverse each section
- Qualitative behaviour from the video footage
- Walking speed from the Pozyx data
- Walking path from the Pozyx data (confirmed by video footage)
- Psychological performance from the questionnaire data

The effective speed is calculated as follows:

$$Effective\ speed = \frac{Shortest\ path\ distance}{Time\ to\ traverse\ path}$$

5.2.2. Individual

This is the base case and occurred under normal conditions. Here, one visually impaired participant (VIP) traversed each section of the platform twice, once forward and once in reverse. This is to identify walking behaviour without interaction from other group members. The fundamental effect of each section layout on mobility can also be ascertained as each section is tested.

5.2.3. Unidirectional Group Flow

Each VIP was placed in a group of up to seven normally sighted participants (NSPs). The group then traversed each section of the platform. Two passes of the platform were conducted, one forward and one reverse. At the start of each section, participants were instructed to engage in either a restricted or unrestricted behaviour. Therefore, one unrestricted pass and one restricted pass were conducted for each section of the platform. This number of participants provided a notable increase in person density on the platform, thus enabling the VIP to remain in crowd conditions as they traversed each section.

5.2.4. Group Opposing Flow

Two groups of up to seven NSPs and one VIP are tested simultaneously. For each section, each group stood on opposing ends of the section and moved towards each other with the aim of reaching the other end of the section. Therefore, there were up to two VIPs and 14 NSPs on the platform at a time. At the start of each section, participants were instructed to engage in either a restricted or unrestricted behaviour. Each section was repeated twice to allow for one unrestricted pass and one restricted pass of each section.

5.3. Working with Participants

VIPs and NSPs were recruited via email, including the mailing lists of visually impaired organisations, online posts, and social media interactions. Throughout recruitment, VIPs were classed as being such through a formal diagnosis of a visual impairment beyond correctable refractive errors (classed as a disability and supported by a CVI). NSPs did not have a visual impairment (beyond correctable refractive errors) and did not identify as being visually impaired (in the context of disability). All participants were over 16 years old and, excluding visual impairment, had no cognitive or mobility impairments.

A script (Appendix A) was read out to participants throughout the experiment to ensure each received equal information on the experiment as it progressed. Moreover, to reduce the impact of changing familiarity with the testing environment, the platform and each test was described in complete detail prior to the start of testing. Participants were also led around the platform to ensure a general knowledge of the testing environment. During experimentation, the research assistant was positioned at the desk and chair on the platform to operate recording equipment, monitor participant safety, and note any variations or observations throughout testing.

Separate questionnaires were produced for VIPs and NSPs, and are included in Appendix B and Appendix C, respectively. Both questionnaires included a section to be completed prior to and following the experiment. All questionnaires asked about age, gender, and previous evacuation experience. For VIPs, additional information was sought on their visual impairment. The post-experiment section aimed to determine the participant's comfortability on each section of the platform during each testing case. These utilised a 5-point Likert scale where one represented the least comfort, and five represented the most comfort.

5.4. Overview of Participants

5.4.1. Overview of Visually Impaired Participants

The experiment ran from 9th April to 11th April 2019. 11 sessions were conducted with a total of 61 participants, 12 of whom were visually impaired. The 12 VIPs that participated in the study had a variety of visual impairments. Table 5.2 lists the basic characteristics of each VIP. The participant ID distinguishes the VIP within each testing session; for instance, 'B2' refers to the 2nd VIP participating in session B.

ID	Gender	Age	Impairment	Aids
A1	M	54	Cataracts, Nystagmus, Detached Retina, Glaucoma	Glasses
A2	M	65	Still's Disease	Long cane
B1	M	65	Retinopathy of Prematurity – Retinal Fibroplasia	Glasses
B2	M	32	Optic Nerve Atrophy	Long cane
C1	M	55	Retinitis Pigmentosa	Long cane
C2	F	60	Retinitis Pigmentosa	Long cane
D1	M	51	Congenital Heredity Endothelial Dystrophy	Long cane
E1	M	52	Retinitis Pigmentosa	Long cane

E2	F	60	Glaucoma, Detached Retina	Glasses, electronic magnifier
F1	M	28	Retinitis Pigmentosa	Long cane
G1	M	59	Glaucoma	Long cane
H1	F	56	Stargardt Disease	Long cane, electronic magnifier

Table 5.2: Overview of the characteristics of the visually impaired participants.

The gender distribution within the test group was 9 males and 3 females. It is anticipated that this had an insignificant effect on mobility relative to the varying impacts on sight caused by the different visual impairments tested, which likely impacted participant behaviour to a much greater extent. Such is reaffirmed by studies conducted by Patel et al. (2006) and Sorensen and Dederich (2015), where participants were divided by visual capability rather than gender and, in the study conducted by Patel et al. (2006), visual field was found to be the primary influence on mobility.

The following table highlights the distribution of ages within this testing group (Table 5.3). An uneven distribution of ages was tested, and this may pose a limitation to the study. However, similarly to the distribution of genders tested, the cause of visual impairment is likely to present a greater impact on the mobility of the participant relative to their age as participants with self-reported physical age-onset mobility problems were excluded from the study (Patel et al., 2006).

Age Group (Years of Age)	**Number of Participants**
Below 20	0
20-29	1
30-39	1
40-49	0
50-59	6
Above 60	4

Table 5.3: Age distribution of the visually impaired participants.

Table 5.4 summarises the self-reported visual function of participants. It is reaffirmed that a clinical assessment would have been preferrable, although this approach was selected as a result of logistical constraints. Participants were asked about their CVI classification (either Sight Impaired (SI) or Severely Sight Impaired (SSI)), then asked to describe if they had (Y) or did not have (N) significant peripheral vision loss (often noted in the CVI), and then asked to rate each visual function according to the following descriptions on a 3-point Likert scale (where 1 is poor, 2 is fair, and 3 is good):

- Acuity (ability to read signs and text)
- Contrast sensitivity (ability to detect poorly lit objects)
- Peripheral vision (seeing objects coming from the side of your vision)

Participants were instructed to judge their visual function according to their perceived function, and that scoring should be relative to each of the visual functions listed considering their own capacity, rather than their perceived capacity of normal vision. The intention was to understand which of the three functions was most valued and used by each participant, and whether a correlation exists between certain perceived functions and mobility within the experiment.

ID	CVI	PVL	Impairment	VA	CS	VF	Avg.
A1	SI	Y	Cataracts, Nystagmus, Detached Retina, Glaucoma	2	2	1	1.7
A2	SSI	Y	Still's Disease	1	1	1	1.0
B1	SSI	Y	Retinopathy of Prematurity – Retinal Fibroplasia	1	1	1	1.0
B2	SSI	Y	Optic Nerve Atrophy	1	1	1	1.0
C1	SSI	Y	Retinitis Pigmentosa	1	1	1	1.0
C2	SSI	Y	Retinitis Pigmentosa	1	1	1	1.0
D1	SSI	N	Congenital Heredity Endothelial Dystrophy	1	1	1	1.0
E1	SSI	Y	Retinitis Pigmentosa	1	1	1	1.0
E2	SI	N	Glaucoma, Detached Retina	1	2	1	1.3
F1	SSI	Y	Retinitis Pigmentosa	1	1	1	1.0
G1	SSI	Y	Glaucoma	1	1	2	1.3
H1	SSI	N	Stargardt Disease	1	1	2	1.3
Avg.				1.1	1.2	1.2	1.1
SD				0.3	0.4	0.4	0.2
CV				26.6	33.4	33.4	19.6

Table 5.4: Self-reported visual function of the VIPs.

In addition to rating their perceived visual function, participants were also asked to freely describe their vision as best as they could. Table 5.5 summaries the results obtained. It is reiterated that clinical visual function testing would have been preferred; however, the qualitative descriptions of visual function by participants was sufficient to separate participants into four groups of decreasing impairment severity, encompassing those with and without light perception, and to better understand the approximate nature of field and acuity loss experienced by each participant:

1. A2, B2, C1, and C2 possessed no light perception, and this is reflected by the minimum visual function scores reported by each.
2. B1 and E1 possessed only the ability to detect whether light was present, and their scores were, similarly to the group with no light perception, at the minimum possible.
3. D1, F1, G1, and H1 commented differently on their visual field, acuity, and scotopic vision, and it is therefore difficult to rank these participants amongst each other according to visual function without further clinical testing.
4. A1 and E2 possessed the best overall visual function within the groups given that they were the only participants registered as SI, and also reported the two highest average visual function scores.

ID	Light Perception	Comments
A1	Yes, similar in both eyes	Slow response to light level change (requires sighted guide in darkened areas). 20/200 VA.
A2	No	-
B1	Yes, similar in both eyes	Can only tell if it is light or dark.
B2	No	-
C1	No	-
C2	No	-

D1	Yes, only in left eye	Very blurry with wide field, enough to count fingers but not enough to see facial details.
E1	Yes, similar in both eyes	Can only tell if it is light or dark.
E2	Yes, different in each eye	Left eye: Macular hole and retinal detachment causing no central vision and cloudy peripheral vision. Right eye: Cataracts causing cloudiness across visual field.
F1	Yes, similar in both eyes	20% of visual field remaining as central vision. Short-range acuity to see faces, but no long-range acuity. Some contrast sensitivity and night vision deteriorating rapidly.
G1	Yes, similar in both eyes	Blurry and dim across visual field deteriorating due to eye pressure. Very poor night vision (lights need to be bright to be able to seem them).
H1	Yes, similar in both eyes	Wide but uneven visual field deteriorating at bottom left and intact at top left (requiring eccentric viewing with eyes positioned at 4 o'clock to use best peripheral vision). Poor short and long-range acuity insufficient for reading. B2 paralympic classification for blind sport.

Table 5.5: Visually impaired participants' description of their vision.

It is noted that the sample size of VIPs limits the statistical significance of the results obtained, particularly in considering the small subgroups of different visual impairments included. To address this, the rigorous testing of each participant through several scenarios and passes increases confidence in the results obtained. Moreover, a wide range of visual impairments is present, therefore allowing for a spectrum of abilities and behaviours to become apparent.

5.4.2. Overview of Other Participants

Table 5.6 represents the NSPs that took part in the study. Similarly to the visually impaired group, more males than females were present (33 males and 16 females).

ID	Age	Gender
AN1	23	M
AN2	21	F
AN3	22	M
AN4	24	M
AN5	23	M
AN6	19	M
AN7	33	F
AN8	25	M
AN9	34	M
AN10	23	M
AN11	40	M

BN1	23	F
BN2	21	M
BN3	22	M
BN4	33	F
CN1	22	M
CN2	39	F
CN3	22	F
CN4	23	F
CN5	26	F
DN1	21	M
DN2	23	F
EN1	21	M
EN2	22	M
EN3	21	F
EN4	22	F
EN5	22	M
EN6	25	M
EN7	21	M
EN8	34	M
EN9	31	F
EN10	42	F
EN11	32	M
GN1	20	M
GN2	23	M
GN3	23	F
GN4	23	M
GN5	22	M
HN1	21	M
HN2	23	F
HN3	23	M
HN4	23	M
HN5	20	M
HN6	24	M
HN7	22	M
HN8	22	M
IN1	23	M
IN2	21	F
IN3	21	M

Table 5.6: Overview of the characteristics of the NSPs.

Unlike the visually impaired group, the ages within the normally sighted group were strongly skewed towards the 20-29-year-old age group, as presented within Table 5.7. This is as several NSPs responded to recruitment via mailing from Imperial College London. A higher likelihood of students and younger people within the sample of NSPs therefore prevailed.

Age Group (Years of Age)	Number of Participants
Below 20	1
20-29	39
30-39	7

40-49	2
50-59	0
Above 60	0

Table 5.7: Age distribution of the NSPs.

Further analysis of the age groups of all participants in Table 5.8 highlights that the NSPs had a significantly younger mean age than the visually impaired participants, paired with a smaller standard deviation but similar coefficient of variation. This is a limitation as crowds in realistic environments are likely to present a broader range of ages than that of the normally sighted group recruited for this experiment. However, given that the purpose of this group is to act as dynamic obstacles with minimal cognitive interaction with visually impaired participants, the effects of age are not considered to limit the outcomes of this study. Moreover, visual impairment is more likely to occur with age, thus resulting in an older VIP sample.

Group	**Age (Years)**		
	Avg.	**SD**	**CV (%)**
VIP	53.1	11.7	22.0
NSP	24.7	5.5	22.3

Table 5.8: Participant age analysis.

5.5. Individual Behaviour

The average time to traverse each section individually for each VIP is presented in Figure 5.3. The time to traverse each section varied significantly for each VIP, evidenced by the mean pass time for all VIPs which was 11.4 s for section 1, 21.4 s for section 2, and 15.8 s for section 3. The 14.6% increase in effective path length between section 1 and section 2 accounts for part of this discrepancy, although the 87% increase in mean time between section 1 and section 2 suggests that the presence of obstacles was significant on mobility. Similarly, while section 1 and 3 had the same effective path length, section 3 presented a 38.6% increase in mean time, corroborating the impact of obstacles on participants.

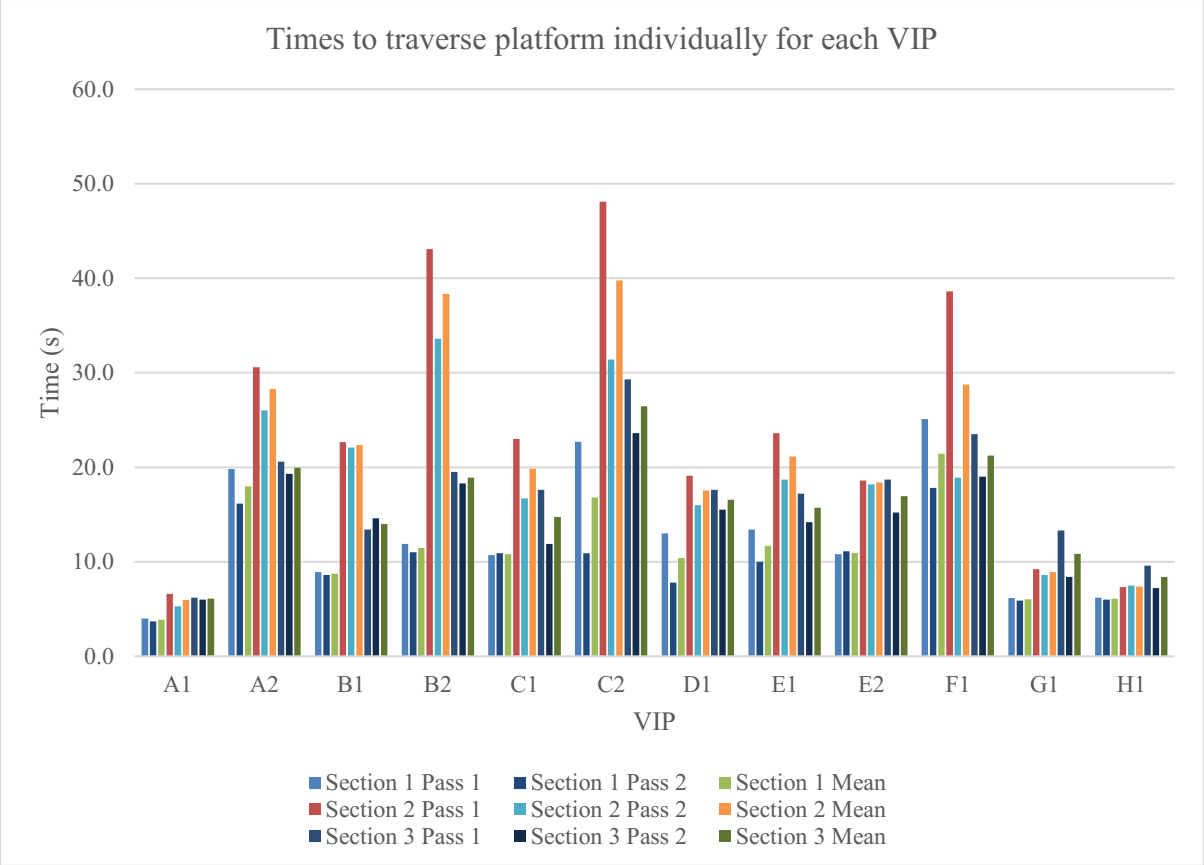


Figure 5.3: Times to traverse platform individually for each VIP.

The Standard Deviations (SD) and Coefficient of Variation (CV) assist in understanding the spread of results. The SD for times to traverse section 1, 2, and 3 were 5.2 s, 11.1 s, and 5.6 s, respectively. The CV for times to traverse section 1, 2, and 3 were therefore 45.7%, 51.7%, 35.6%. These are high CVs, suggesting significant dispersion within the results between each VIP for all sections. Interestingly, while section 1 presents a lower mean time to traverse the platform than section 3, section 3 yields results with smaller dispersion. Ground-level obstacles therefore generally affected all VIPs. Section 2 presented the highest dispersion, suggesting variability in the extent to which the maze-like walking path affected VIPs.

Figure 5.3 also shows that second passes of each section were typically faster than the first. This concurs with the positive effect of familiarity on mobility. Indeed, for section 1, VIPs demonstrated a mean percentage change of -15.5% between time to complete pass 1 and pass 2. Only 2 of 12 VIPs demonstrated a positive percentage change (1.9% and 2.8%), although these were small and could be considered within margin of error. Similarly, for section 2, VIPs demonstrated a mean percentage change of -17.9% (with only H1 showing a negligible increase of 2.7%). Finally, for section 3, a mean percentage change of -15.6% was observed, although B1 required 9% longer to complete pass 2. This strongly suggests that, as participants repeat an activity, their ability to do so effectively increases. This concurs with findings from the literature.

In the following analysis, the mean of both passes for each section is considered as the baseline for each VIP. This is as VIPs are likely to encounter a multitude of familiar and unfamiliar environments in daily mobility, and this is assumed to be reflected by considering both passes when comparing results. Figure 5.4 details the calculated effective walking speed of VIPs.

Similar overall conclusions can be made to those for walking times given that the calculation for walking speed involved the division of the shortest path distance (a constant for each section) by the walking time.

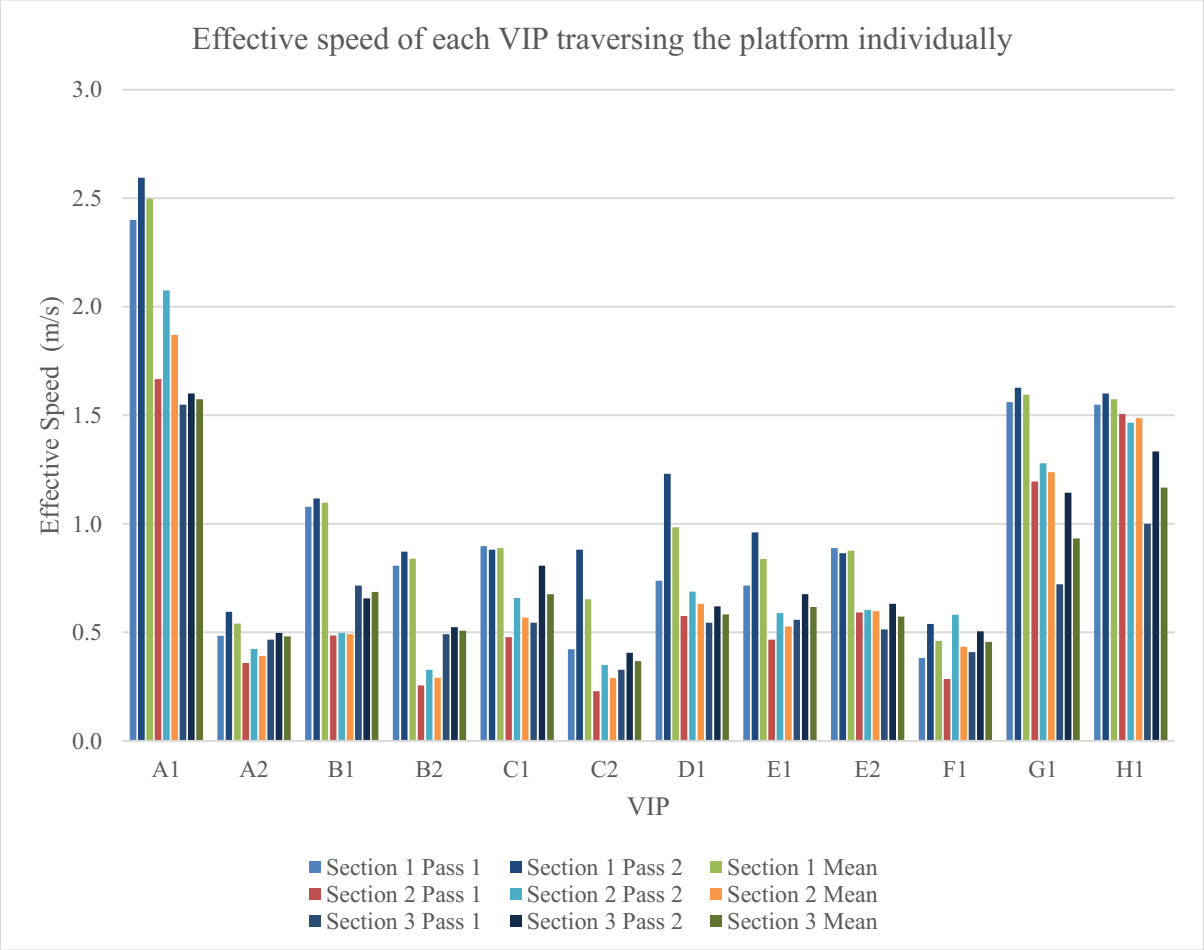


Figure 5.4: Effective speed of each VIP traversing the platform individually.

The mean effective walking speed of VIPs was 1.1 m/s for section 1 (SD = 0.6 m/s, CV = 53.3%), 0.7 m/s for section 2 (SD = 0.5, CV = 69.5%), and 0.7 m/s for section 3 (SD = 0.3 m/s, CV = 48.3%). The significantly elevated CV suggests a large spread of results, and section 1 presents the highest mean effective speed with the least variation. Section 2 and 3 present lower mean speeds, with section 3 yielding a smaller spread of results than section 2. However, further analysis of each VIP's behaviour from the video footage and automated data collection highlights behavioural differences beyond reductions in effective walking speed.

This is exemplified when comparing B1 and B2's performance. It can be seen that B2 displays a slower effective walking speed than B1 in all sections. In section 2, B2 approximately doubles the time required by B1 to traverse the platform. This is expected as B2 presents no light perception while B1 has only light and dark perception. Figure 5.5 presents the walking path plots for B1 and B2 for their first pass of the platform.

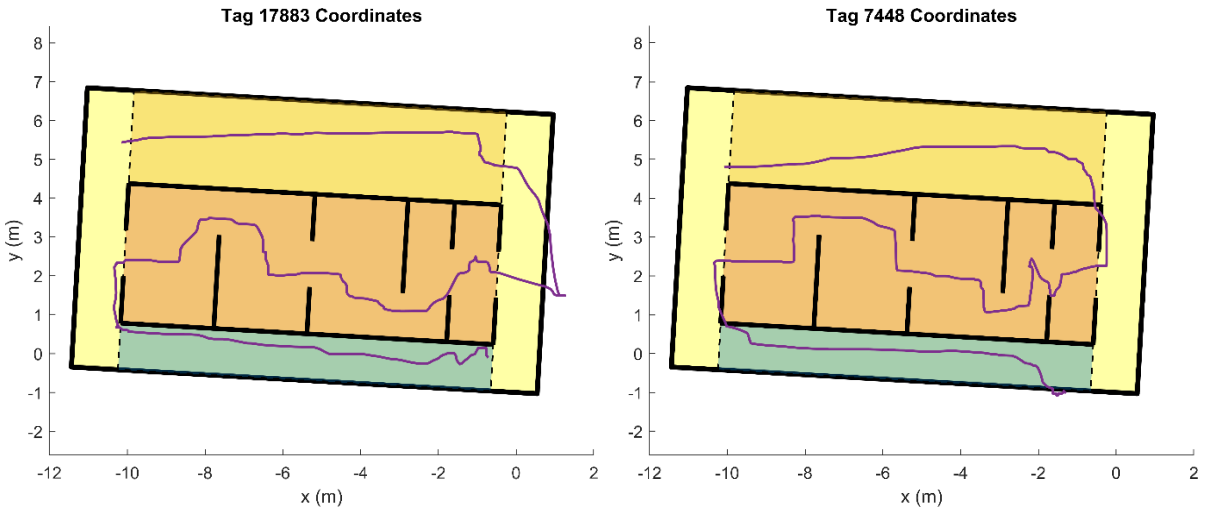


Figure 5.5: Plot of B1 (left) and B2's (right) walking path across their first pass of the platform.

Results beyond the dashed line should be ignored as positioning uncertainty rose significantly beyond the boundaries of the walking path. Data smoothing using a moving median of 30 data points was iterated to present a clearly defined path similar to that observed from the video footage. All sections presented slightly worse path efficiencies for B2 versus B1, with the largest variation noted in section 2. B1 appeared to use their residual sight to navigate through the openings, while B2 made sudden directional changes observable from the right-angled path curvatures occurring through touching walls. Consequently, for section 2, B1 walked a distance of 12.8 m, yielding a path inefficiency of 15.9% while B2 walked a distance of 15.3 m with 39.4% path inefficiency. Figure 5.6 denotes the walking speeds of B1 and B2 for their first pass of the platform.

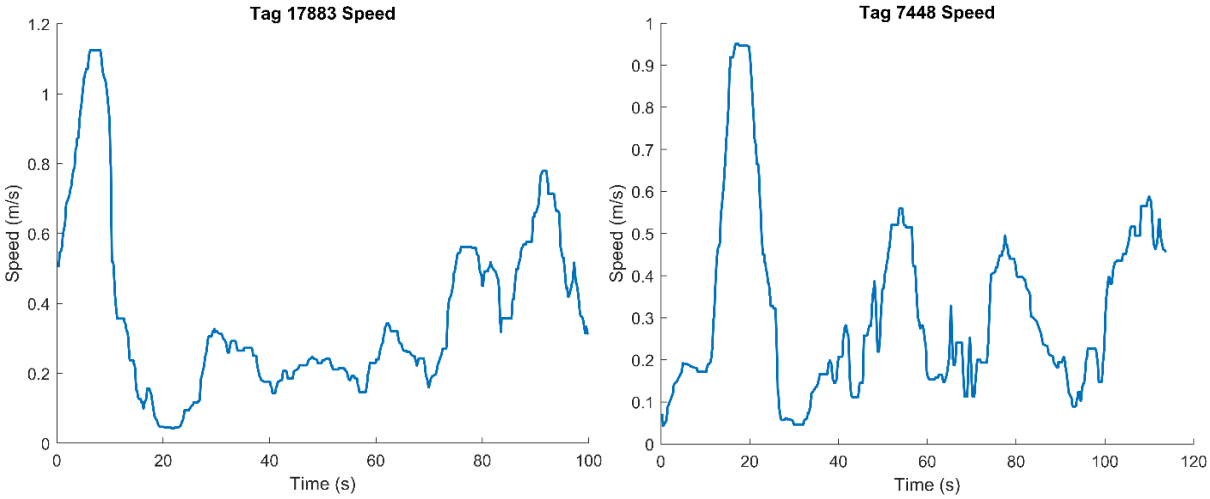


Figure 5.6: Plot of B1 (left) and B2's (right) walking speed across their first pass of the platform.

Peak walking speeds were slightly elevated for B1 in section 1 (1.12 m/s versus 0.97 m/s) and section 3 (0.78 m/s versus 0.6 m/s). This was not true for section 2, however, where B1 presented a lower peak walking speed of 0.32 m/s versus 0.51 m/s for B2. Similarly, B1 had a lower mean speed of 0.27 m/s versus 0.33 m/s for B2. However, B1 performed significantly better in effective walking speed; their lower speed was maintained more consistently than B2 where, instead, significant peaks and troughs in walking speed can be observed. This coincides

with the more aggressive changes in direction by B2 resulting in reduced path efficiency in section 2.

Finally, the confidence reported by VIPs coincides with their own performance across each section individually. In the example of B1 and B2, B1 had a higher average reported confidence than B2 (4.0 versus 3.3). Interestingly, B2's confidence dipped significantly for section 2 (scoring a 2) versus section 1 and 3 (scoring a 4), coinciding with B2's erratic walking behaviour in section 2. Contrarily, B1 scored a 5, 4, and 3 for section 1, 2, and 3, respectively. Figure 5.7 displays the mean effective speed for each section versus comfort score for all VIPs individually traversing the platform.

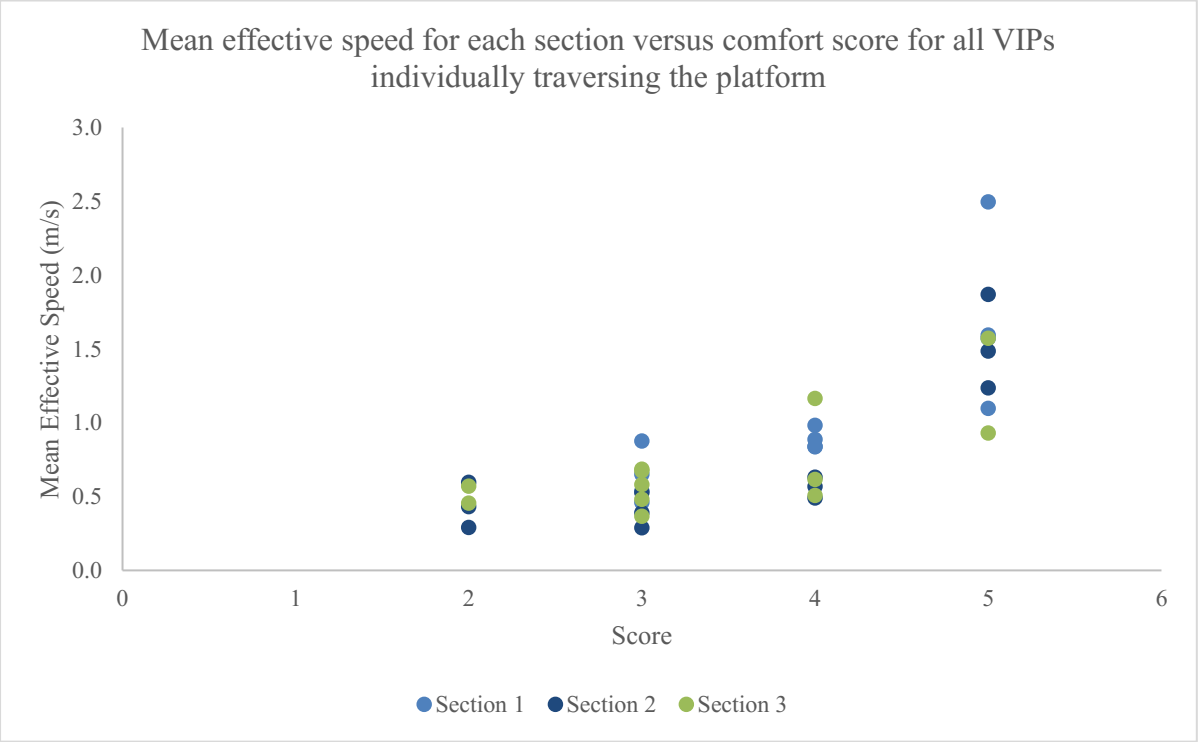


Figure 5.7: Mean effective speed for each section versus comfort score for all VIPs individually traversing the platform.

There was a positive correlation between confidence and walking speed between sections. Section 1 presented the highest mean confidence at 4.0 (SD = 0.9, CV = 21.3%), followed by section 2 at 3.5 (SD = 1.2, CV = 33.4%), and section 3 at 3.4 (SD = 1.0, CV = 29.2%). This coincided with the order of decreasing mean effective speed for each section. It can therefore be concluded that the introduction of obstacles hindered VIP performance and self-reported confidence, especially smaller ground level obstacles. Visually observation of Figure 5.7 highlights that, while mean speed does indeed increase with perceived comfort, so does the dispersion of results. Section 1's relatively high mean comfort and low CV exemplifies this. Figure 5.8 introduces the mean effective speed versus mean effective comfort score for each VIP.

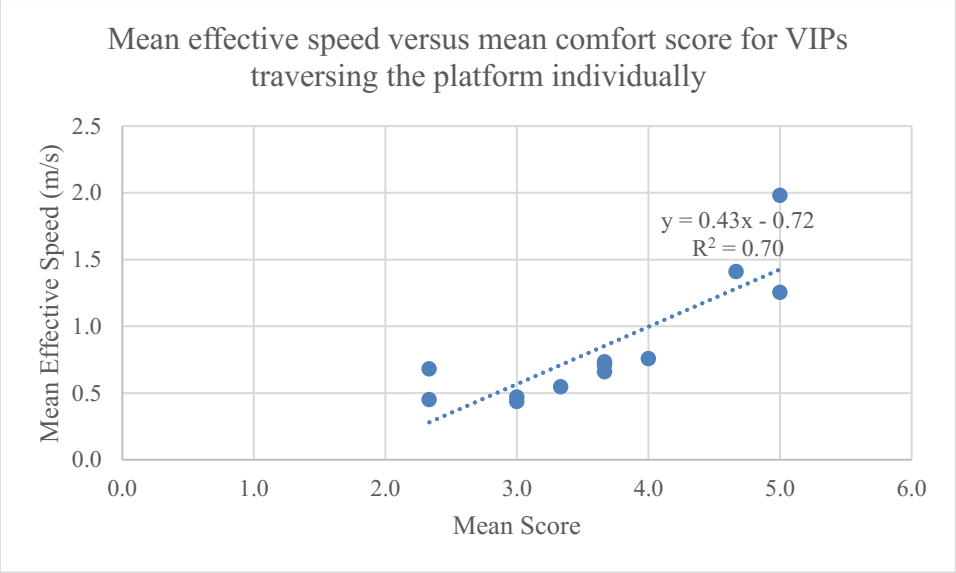


Figure 5.8: Mean effective speed versus mean comfort score for VIPs traversing the platform individually.

The line of best fit for mean effective speed against mean score is determined to have equation:

$$\overline{v_0} = 0.43\bar{S} - 0.72$$

Where $\overline{v_0}$ is the mean effective individual walking speed, and $\bar{S}$ is the mean comfort score. This result is presented with a coefficient of determination (R^2) of 0.70, suggesting a moderately strong positive correlation between mean score and mean effective walking speed for VIPs operating individually.

For comparison to the individual mobility of NSPs, Figure 5.9 displays the average time to traverse each section for the 5 NSPs tested. The mean pass time for section 1 was 6.6 s (SD = 0.7 s, CV = 10.8%), section 2 was 7.7 s (SD = 1.3, CV = 17.4%), and section 3 was 6.8 s (SD = 0.8 s, CV = 11.1%). The performance of NSPs for each section was therefore far more consistent than that of the VIPs. Moreover, and as expected, the NSP times fell significantly below the VIP times.

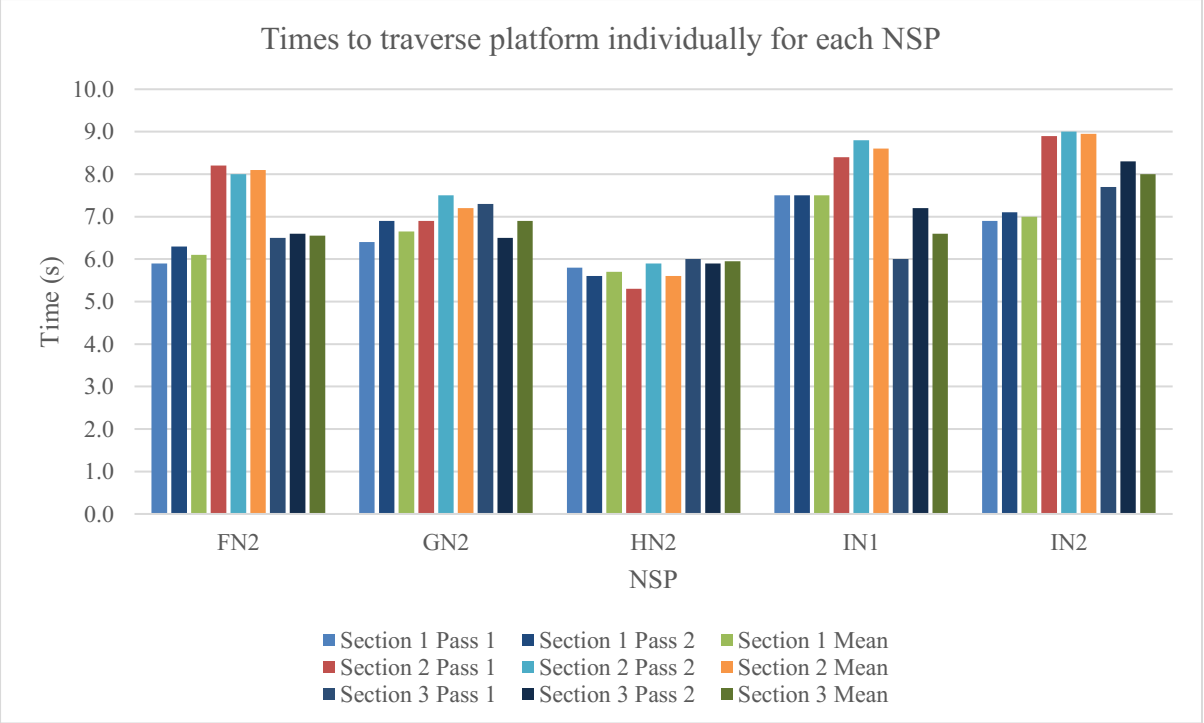


Figure 5.9: Times to traverse platform individually for each NSP.

Another notable phenomenon is that the variance in time between each section for an NSP is typically much lower than that for a VIP. This signifies the unique spatial orientation challenges faced only by VIPs in different environments which have yet to be simulated in existing models. The NSPs did not show consistent improvement in their second pass of each section. Rather, differences between performance in each pass could be considered within margin of error; the mean percentage difference between passes was 2.8%, 4.7%, and 3.3% for section 1, 2, and 3, respectively. Visual perception therefore presided over increasing familiarity in determining performance. This translated to the effective walking speeds of NSPs, as presented in Figure 5.10.

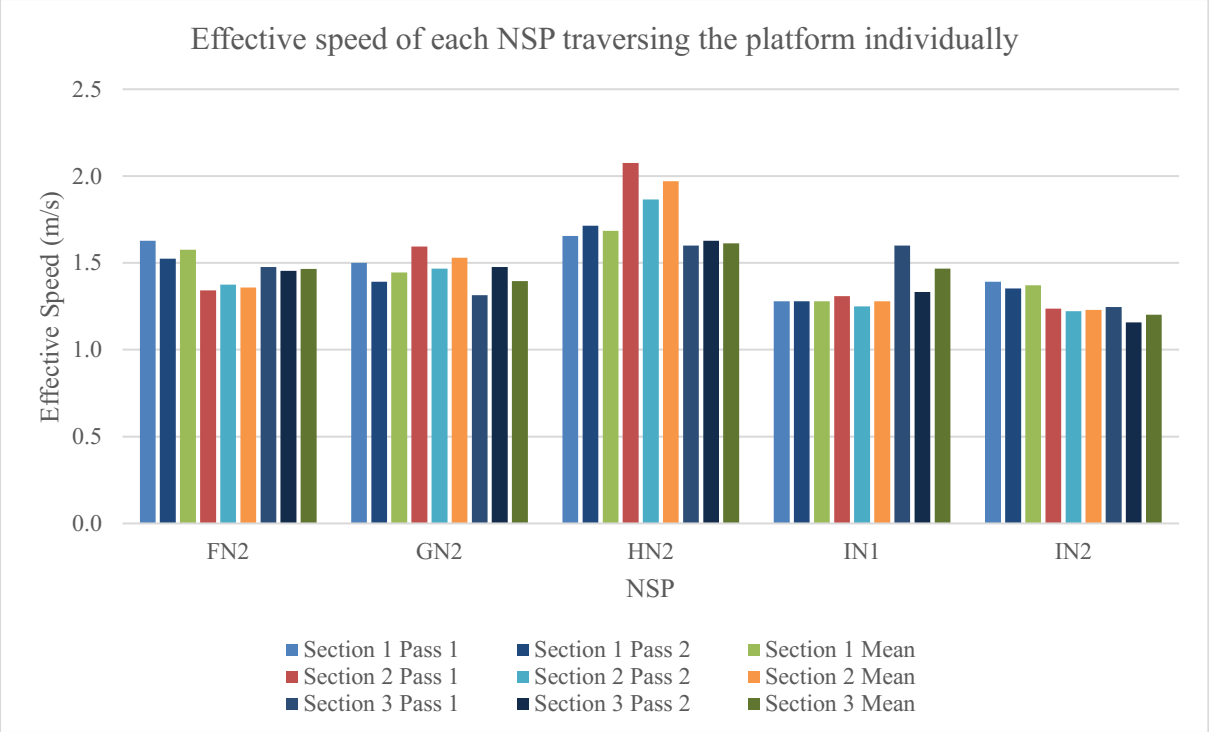


Figure 5.10: Effective speed of each NSP traversing the platform individually.

The mean effective walking speed of NSPs was 1.5 m/s for section 1 (SD = 0.2 m/s, CV = 10.9%), 1.5 m/s for section 2 (SD = 0.3, CV = 20.4%), and 1.4 m/s for section 3 (SD = 0.1 m/s, CV = 10.5%). While slightly higher variation in effective speed is evident in section 2, NSPs maintained their own consistent effective speed across sections, as demonstrated by similar mean effective speeds obtained for each section. Further analysis of the video footage and automated data collected highlights that discrepancies in effective speed were not a result of inefficient walking paths (as was the case with VIPs), but rather each NSP maintaining their preferred speed across an effective path through each section. This is demonstrated through the walking paths of GN2 and IN2, for example, as shown in Figure 5.11.

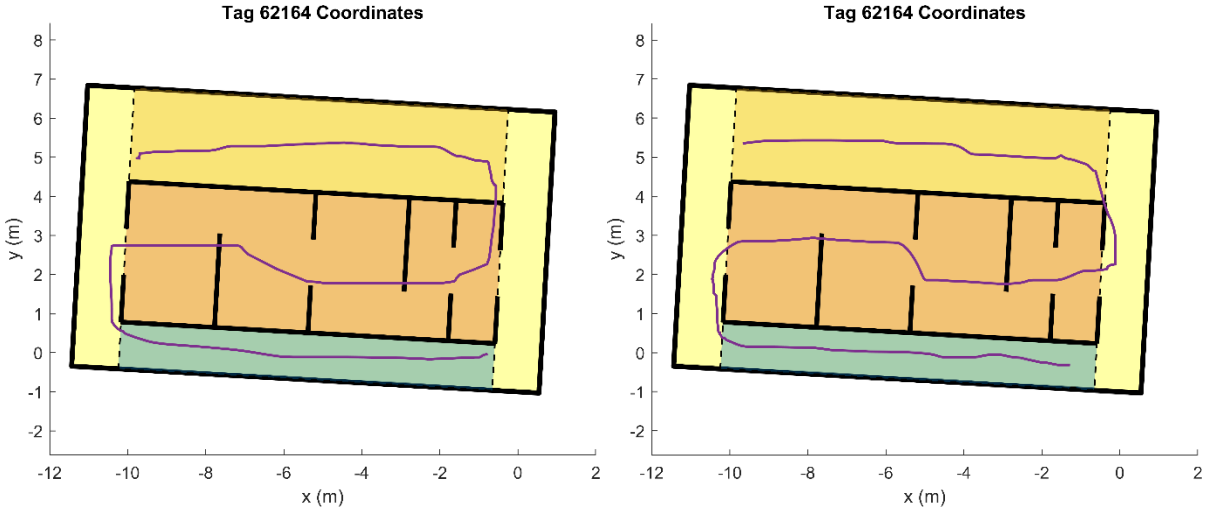


Figure 5.11: Plot of GN2 (left) and IN2's (right) walking path across their first pass of the platform.

As in the case of the walking paths generated for VIP B1 and B2, results at section boundaries are ignored given the positioning system's artifacts within these regions. The same data

smoothing was used to ensure fairness of comparison. Other than the sharper and earlier turn made by IN2 in the middle of section 2, both NSPs' walking paths were significantly more efficient than that of the VIPs, with each NSP walking within centimetres of wall edges (as can be seen in the overlapping path lines with section 2's boundaries). Figure 5.12 shows the walking speeds of GN2 and IN2 across the platform.

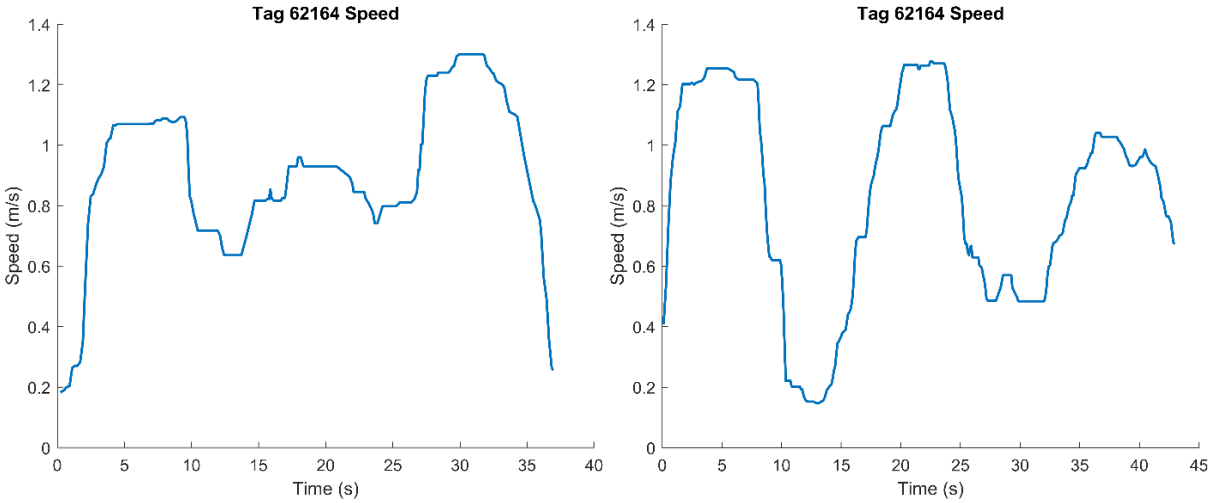


Figure 5.12: Plot of GN2 (left) and IN2's (right) walking speed across their first pass of the platform.

Dissimilarly to the VIPs, visibly clear and sustained peaks were observed for each section. For GN2, this approximated to a sustained 1.1 m/s for section 1, 0.9 m/s for section 2, and 1.2 m/s for section 3, while IN2 sustained 1.2 m/s for sections 1 and 2, and 1.0 m/s for section 1. The two valleys between the three peaks (representing each section) varied for each NSP as GN2 transitioned between sections more quickly than IN2, but this was not considered as part of the testing. Observation of section 2's walking paths demonstrates the differences in path efficiency between the NSPs and VIPs. GN2 and IN2 both walked 10.1 m-long paths, an 8.6% more efficient path than the optimal path of 11.0 m calculated assuming traversal through the midpoint of each opening in section 2's maze walls.

5.6. Unidirectional Group Flow

5.6.1. Unrestricted Unidirectional Group Flow

As conducted in the analysis of individual behaviour, group behaviour is primarily observed (and walking metrics calculated) from the video footage. The time to traverse the platform under all group conditions for each VIP is found, as is the effective speed. The automated data collected is then utilised to further detail specific behaviours seen throughout the video footage. In combination with the questionnaire data, this allows for a comprehensive analysis of the physiological and psychological aspects of the experiments.

Figure 5.13 highlights the time to traverse the platform required by each VIP in an unrestricted unidirectional group flow. The results between VIPs had a broad spread, as seen in the analysis of individual behaviour. The mean time to traverse section 1 was 10.5 s (SD = 4.4 s, CV = 41.8%), section 2 was 19.1 s (SD = 10.9 s, CV = 57.1%), and section 3 was 12.4 s (SD = 4.4 s, CV = 35.2%). In comparing to the individual flows, this represented mean decreases of 0.9 s, 2.3 s, and 3.4 s for section 1, section 2, and section 3, respectively.

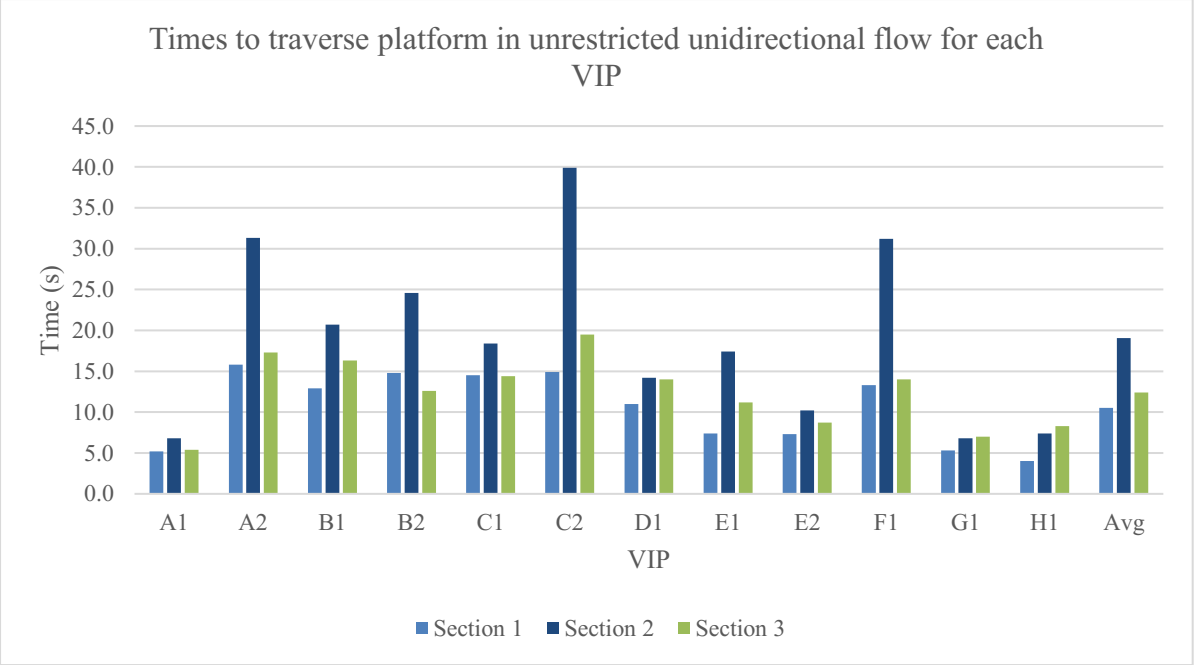


Figure 5.13: Times to traverse platform in unrestricted unidirectional flow for each VIP.

Figure 5.14 presents the effective speed of VIPs traversing the platform in unrestricted unidirectional flows. The mean effective walking speed of VIPs was 1.1 m/s for section 1 (SD = 0.6 m/s, CV = 53.3%), 0.8 m/s for section 2 (SD = 0.5 m/s, CV = 62.3%), and 0.9 m/s for section 3 (SD = 0.4 m/s, CV = 43.4%). Section 1 therefore continued to present the best average effective performance for VIPs, followed by section 3, and then section 2. This differs to performance when moving individually where section 2 and section 3 presented identical effective speeds. Although, the 0.1 m/s mean difference in performance between these sections introduced by the unrestricted unidirectional flow can be considered to be within margin of error. The performance increase in introducing the unrestricted unidirectional flow of 0.1 m/s and 0.2 m/s for section 2 and section 3, respectively, remains surprising; the introduction of crowds, according to literature, should have had the inverse effect.

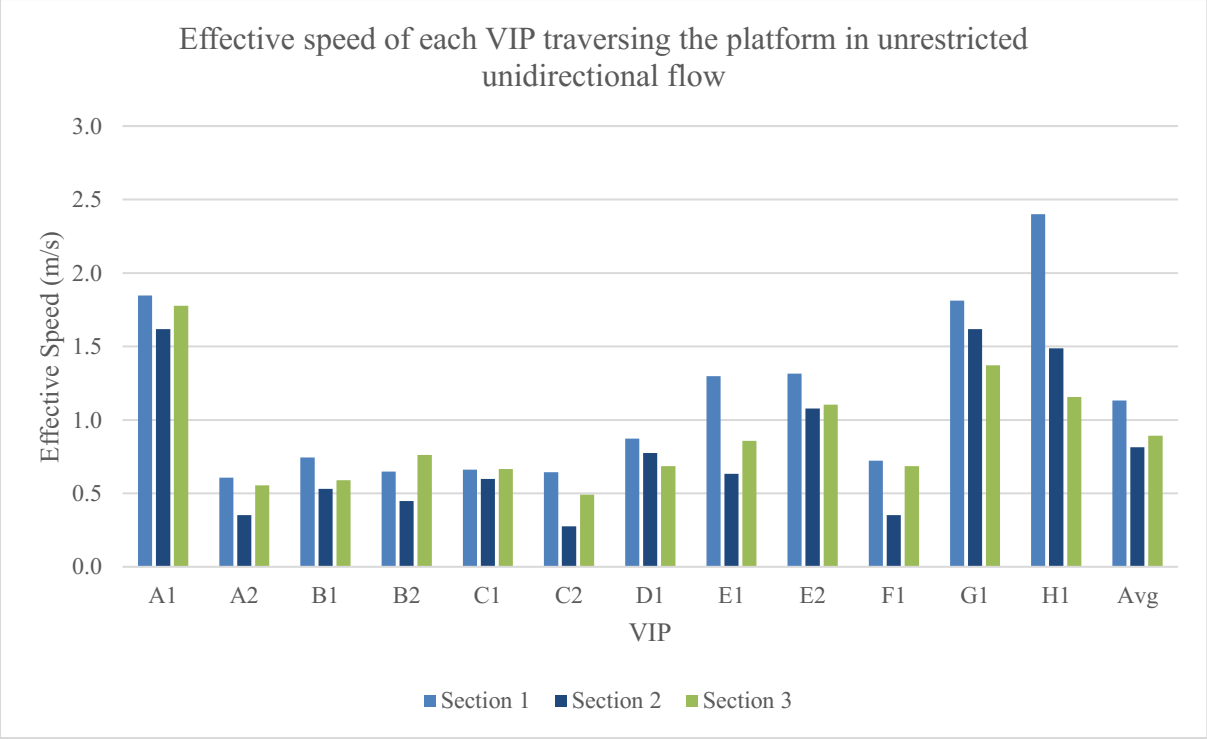


Figure 5.14: Effective speed of each NSP traversing the platform in an unrestricted unidirectional flow.

While it can therefore be assumed that the introduction of an unrestricted group flow may increase VIP performance in areas with large and small obstacles, further analysis of the spread of the data demonstrates that this is not consistent. It is also environment-dependant; in section 1, the introduction of the unrestricted unidirectional flow decreased the CV by 3.9% whereas in section 2, the CV increased more significantly by 5.4%. In section 3, the CV decreased insignificantly by 0.4% (although this is considered within margin of error), Figure 5.15 displays the percentage change between times to traverse the platform individually and in unrestricted unidirectional flow for each VIP.

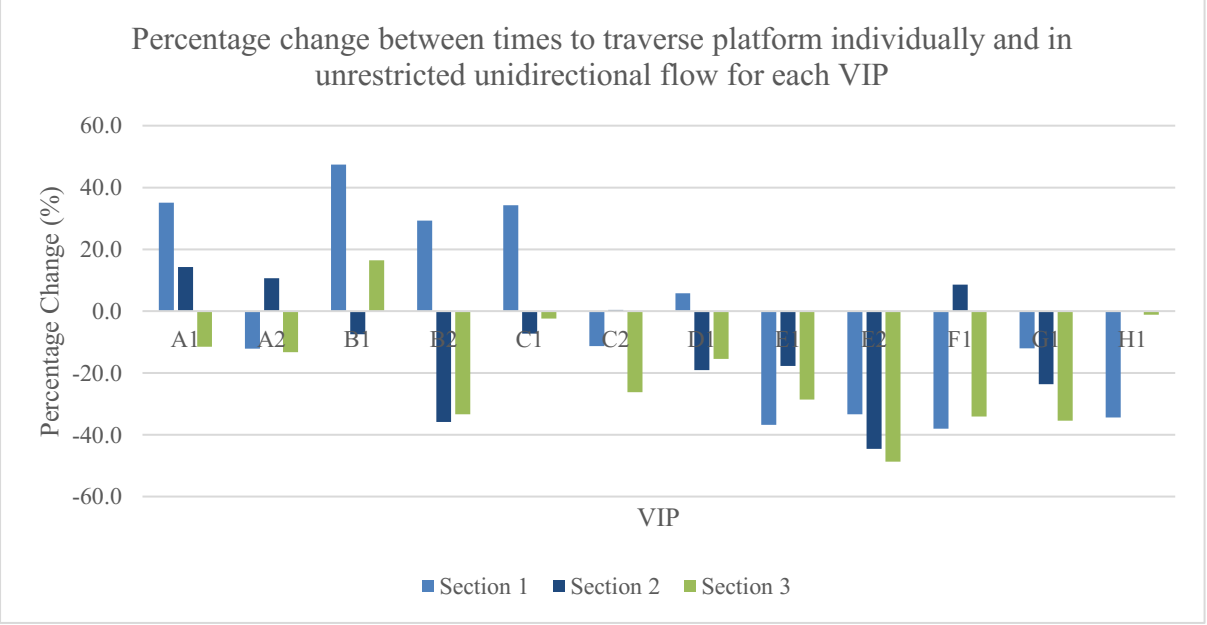


Figure 5.15: Percentage change between times to traverse platform individually and in unrestricted unidirectional flow for each VIP.

Only 3 of 12 VIPs demonstrated an average increase in time to complete all 3 sections in an unrestricted unidirectional flow versus individual performance; these were A1, B1, and C1 with average percentage changes of 12.6%, 18.8%, and 8.2%, respectively. This could not be correlated with visual function as these VIPs belonged to Group 1, 2, and 4 in considering visual impairment severity. The remainder of VIPs experienced, on average, better performance, although not consistently across sections. For instance, A2 required more time to complete section 2 in the unrestricted unidirectional flow versus individually, but less time in section 1 and section 3. B2 required more time in section 1, but less time in section 2 and 3. E1, E2, and G1 required less time to complete all sections versus individual performance.

Further analysis of the crowd's behaviour in the video footage provides reasoning as to why these changes in performance occurred, particularly in section 3 where the largest average percentage change in performance was observed. The unrestricted nature of the flow encouraged participants to overtake others if needed. Section 3 had a width of 2.4 m whereas section 1 was restrictive in its width of 1.2 m. Individuals were therefore able to move around the VIP more freely in section 3, overtaking without impeding the VIP's direct line of motion. This behaviour is depicted by Figure 5.16 where a snapshot is taken from the same VIP operating in section 1 and section 3.



Figure 5.16: Group overtaking behaviour in an unrestricted unidirectional flow in section 1 (left) and section 3 (right).

This behaviour resulted in collisions occurring between the VIP and other group members; group members attempted to overtake the slower moving VIP in all cases, and this appeared to be independent of the width of the section. Figure 5.17 demonstrates one such occurrence with VIP F1 and an NSP attempting to overtake through an 0.4 m-wide gap. F1's cane collided with the NSP's leg, leading to a complete stop of F1 as they became disorientated. F1 then proceeded at a slower walking speed than prior to the collision, resulting in F1 requiring 8.5% longer to complete this pass of section 2 relative to their individual performance.

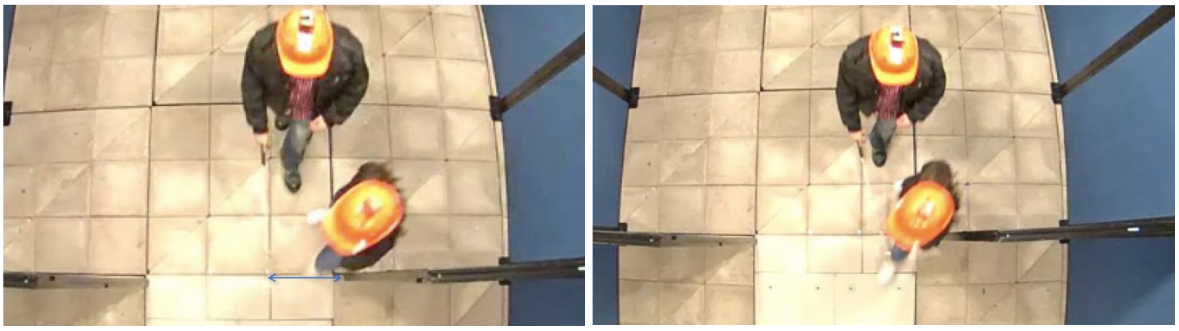


Figure 5.17: NSP colliding with a VIP's cane while attempting to overtake through a small gap.

Figure 5.18 exemplifies how the overtaking behaviour of group members slowed down others within the group. Here, an NSP attempted to overtake B1, but collided with B1's cane. The NSP then turned back to assess their impact on the VIP, to which both the VIP and NSP stopped and restricted all members behind them. After two seconds, motion restarted where the NSP stepped behind the VIP and overtook from the opposite direction. This left the VIP visibly disorientated for another two seconds while other members of the group followed the clear path led by the NSP.



Figure 5.18: Collision, stop, and go wave created by an NSP colliding with a VIP while overtaking them in section 2.

Irrespective of this initial inefficiency, B1 continued to complete this pass of section 2 7.5% faster than they had done individually. This was a result of the collisions, brushing, and touching arising from participants as they overtook the VIP. This led to 'bounce' and push the VIP through openings, and in the correct direction. Figure 5.19 highlights two distinct examples; the two leftmost images are of an NSP continuously placing their hand and guiding B1, while the NSP in the rightmost image briefly placed their hand on D1 while overtaking to prevent a harder collision. This caused the VIPs in both examples to speed up and slightly shift direction to clear the openings within section 2.



Figure 5.19: NSP touching a VIP while attempting to overtake them in an unrestricted unidirectional flow in section 2.

This behaviour had profound impacts on certain group members depending on their position relative to the VIP. Figure 5.20 demonstrates the walking path and speed of the NSP that guided B1. This NSP was caught behind B1 for approximately 5 seconds as the first NSP collided with the VIP. The NSP's walking speed was within 0.5 m/s for this duration, accelerating to 0.8 m/s prior to having to reduce speed as they started to guide the VIP, slowing down further as other NSPs within the group created congestion within the final opening of section 2. Interestingly, this NSP continued to walk a very effective path of 11.0 m length, albeit requiring 21 s to traverse section 2 at a mean speed of 0.52 m/s, a much-reduced speed than the individual NSP control passes, and matching B1's performance. Another NSP immediately behind this NSP demonstrated identical performance given that they were not able to overtake the coupled NSP and VIP's combined width.

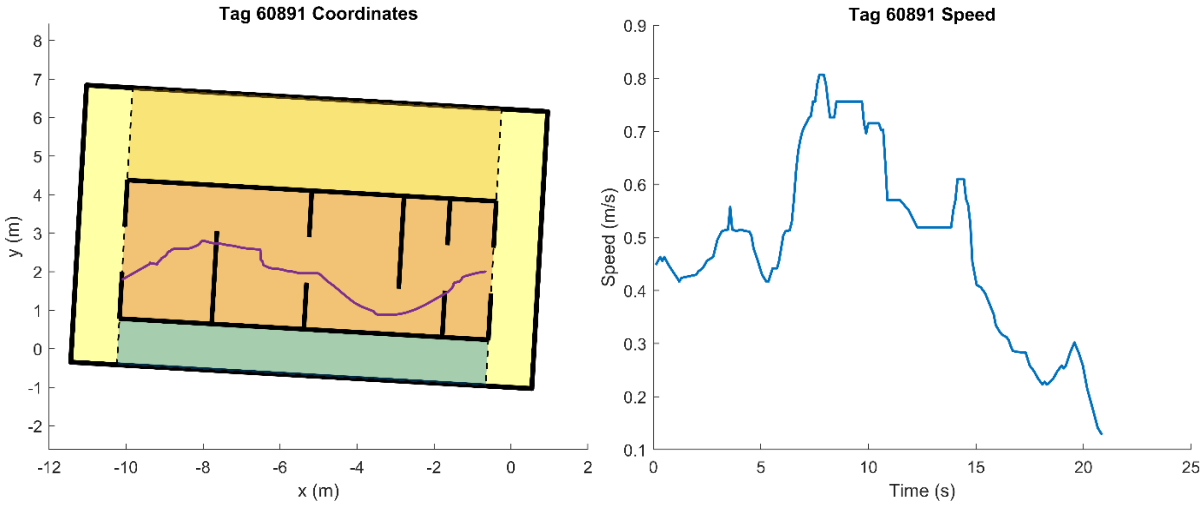


Figure 5.20: NSP guiding VIP in an unrestricted unidirectional flow in section 2.

The other NSPs behind B1 that opted to overtake following the initial NSP-VIP collision demonstrated much improved performance, presenting results within 50% of the NSPs that did not overtake B1. Figure 5.21 highlights one such example where an NSP had to reduce their speed within 0.6 m/s while behind B1 prior to the collision, briefly accelerating to 0.9 m/s to overtake prior to slowing down to complete the section. A single NSP positioned in front of B1 at the start of this pass completed the session in 6.6 s at an effective speed of 1.7 m/s. This NSP traversed the section individually while avoiding all interaction with the group behind them.

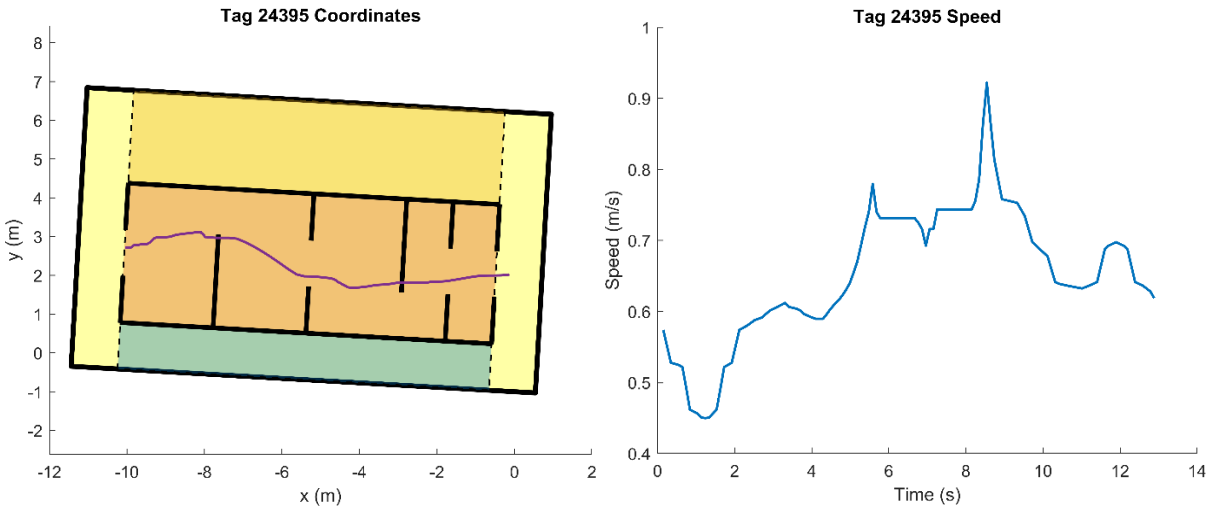


Figure 5.21: NSP slowing down then accelerating to overtake a VIP in an unrestricted unidirectional flow in section 2.

It was often observed that, when NSPs had the opportunity to overtake the VIP, this opportunity was taken in unrestricted unidirectional flows. This was prevalent for VIPs with the worst visual function (groups 1 and 2). Subsequently, these VIPs typically traversed the platform alone, as did VIP C2 in section 2 (Figure 5.22) as NSPs made use of the 3.6 m maximum section width to overtake. As in the example of VIP B1, NSPs initially positioned behind C2 maintained a slower speed, matching C2, but then accelerated to speeds exceeding 1 m/s to overtake and complete the pass. This was not the case for VIPs with better visual function, particularly VIP A1 where performance was indistinguishable from other group members.

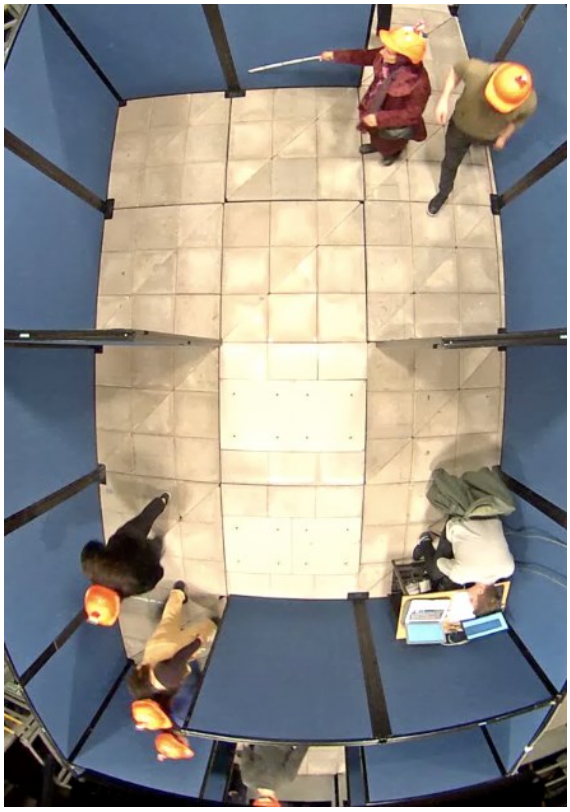


Figure 5.22: VIP traversing the platform individually after being overtaken by all other group members in an unrestricted unidirectional flow in section 2.

These VIPs often used the boundaries of the environment around them to navigate, especially in section 2 as their path closely followed that of the surrounding walls, resulting in sudden movements and path inefficiencies. This behaviour can also be observed in Figure 5.22 where C2 turns sharply towards the wall upon navigating the opening, temporarily facing the opposite direction of travel to tap the wall behind them with their cane, giving the NSP an opportunity to overtake.

Overtaking behaviour of this nature was problematic in cases with more confident and faster moving VIPs, as evidenced in Figure 5.23 depicting H1 operating within section 3 in an unrestricted unidirectional flow. H1 was a fast-moving VIP, often remaining within the group in section 1 and 2. The collision of their cane with a foam block caused an abrupt stop in section 3 for 2 seconds, leading the NSPs moving behind H1 to quickly react and part into two lanes to overtake without collision. This caused a turbulent flow and led to H1 having to operate on their own for the remainder of the pass.

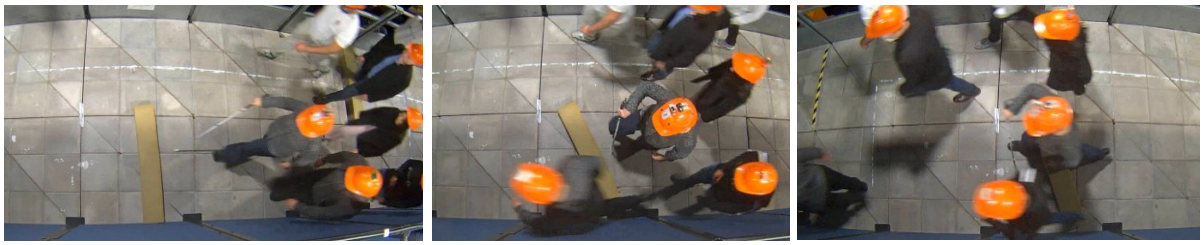


Figure 5.23: A VIP's sudden stop in an unrestricted unidirectional flow in section 3, leading to overtaking, flow turbulence, and the VIP to fall behind the group.

Both positive and negative VIP walking behaviours have therefore arisen on the introduction of group unrestricted unidirectional conditions. This impacted VIP's psychological performance. On analysis of the questionnaire results, 25% of VIPs (B2, C1, and H1) felt more comfortable when traversing the platform on their own than in a unidirectional group. Contrarily, 50% of VIPs felt more comfortable when operating in a unidirectional group than on their own. Figure 5.24 represents the mean effective speed for each section versus mean comfort score for VIPs.

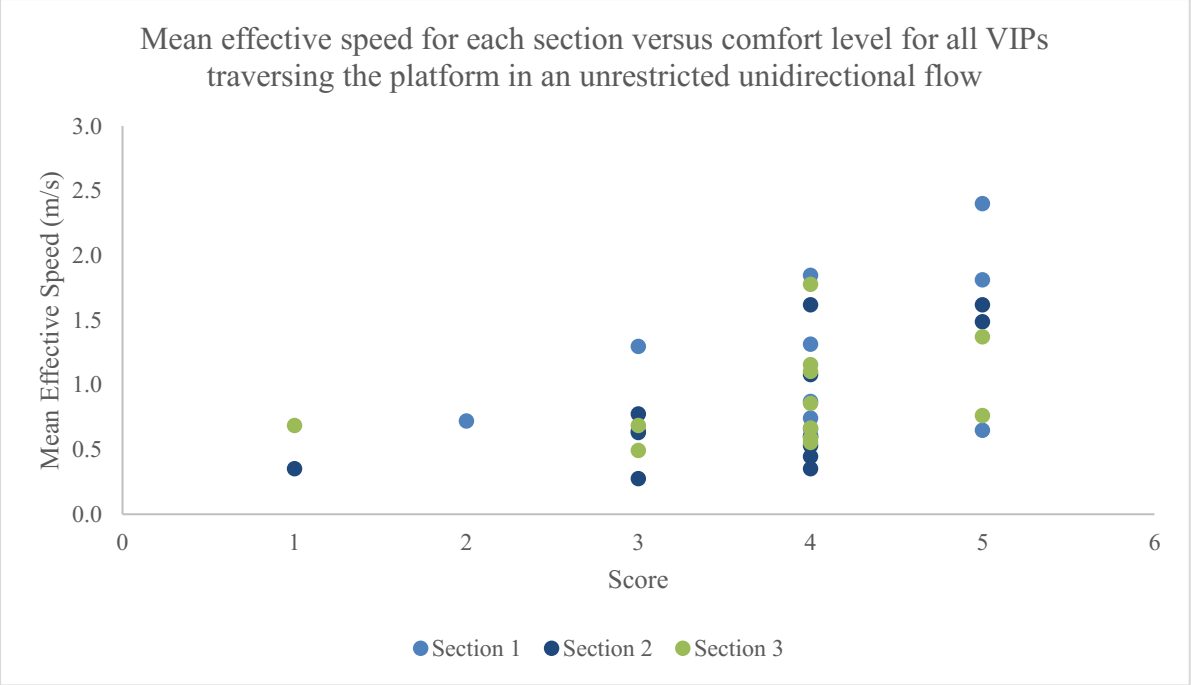


Figure 5.24: Mean effective speed for each section versus comfort score for all VIPs traversing the platform in an unrestricted unidirectional flow.

As observed in individual performance, there was a positive correlation between confidence and walking speed between sections in unidirectional flows. The spread of effective walking speeds also increased as confidence increased. Moreover, the lowest scoring limit in unidirectional flows (two scores of one) was less than that of individual performance (five scores of two). Contrarily, more participants scored above 3 in unidirectional flows than when operating individually, thus reaffirming that group conditions, while not necessarily detrimental to VIP performance, do create a larger spread of performance that can negatively impact certain VIPs.

Section 1 continued to present the highest mean confidence at 3.9 (SD = 0.9, CV = 23.0%), which is 0.1 less than the result obtained individually, albeit maintaining a similar SD and CV. Unlike individual performance, this was followed by section 3, rather than section 2, which presented a mean score of 3.8 (SD = 1.1, CV = 28.1%), a score 0.4 points greater than that of individual performance, although with a slightly higher SD, but lower CV (considered to be within margin of error). Section 2 then had a mean score of 3.7 (SD = 1.1, CV = 29.3%), a score 0.2 higher than that of individual performance, as well as presenting a slightly lower SD and CV of 0.1 and 4.1%, respectively. Figure 5.25 displays the relationship between the mean effective speed versus mean effective comfort score for each VIP in an unrestricted unidirectional flow.

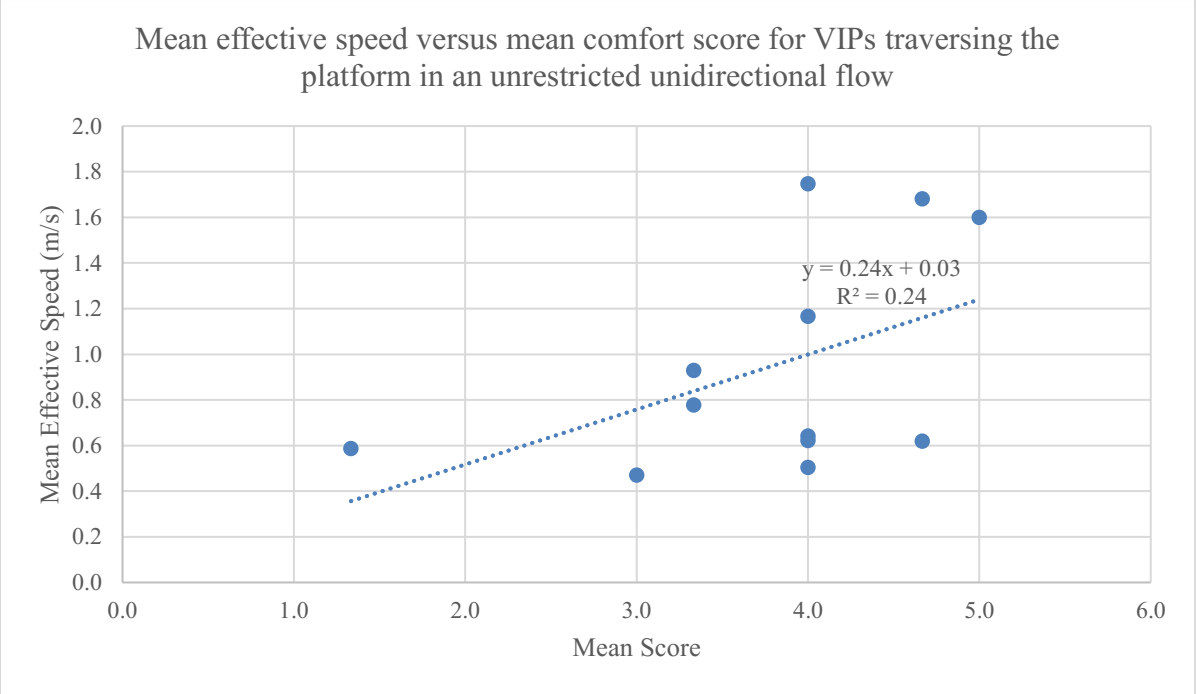


Figure 5.25: Mean effective speed versus mean comfort score for VIPs traversing the platform in an unrestricted unidirectional flow.

The line of best fit for mean effective speed against mean score is determined to have equation:

$$\overline{v_0} = 0.24\bar{S} + 0.03$$

Where $\overline{v_0}$ is the mean effective individual walking speed, and $\bar{S}$ is the mean comfort score. This result is presented with a coefficient of determination (R^2) of 0.24, suggesting a weak positive correlation between mean score and mean effective walking speed for VIPs operating in unrestricted unidirectional flows. Furthermore, this trendline presents a gradient that is approximately 55% of that for individual performance. The weaker correlation is likely to have contributed to this, but this remains to affirm that the introduction of group scenarios generates instability in the physiological and psychological performance of VIPs.

5.6.2. Restricted Unidirectional Group Flow

Restricted and unrestricted unidirectional group flows were conducted in identical VIP-NSP groupings. The results between the different types of unidirectional flow can therefore be fairly compared as the only variable that was changed was the instruction to participants to engage in either an unrestricted or restricted flow. Figure 5.26 highlights the time to traverse the platform required by each VIP in a restricted unidirectional group flow. The mean time to traverse section 1 was 12.2 s (SD = 4.8 s, CV = 39.3%), section 2 was 21.5 s (SD = 9.9 s, CV = 45.9%), and section 3 was 14.3 s (SD = 6.4 s, CV = 44.6%). In comparing to the individual flows, this represented a mean increase of 0.8 s for section 1 and 0.1 s for section 2, and a mean decrease of 1.5 s for section 3.

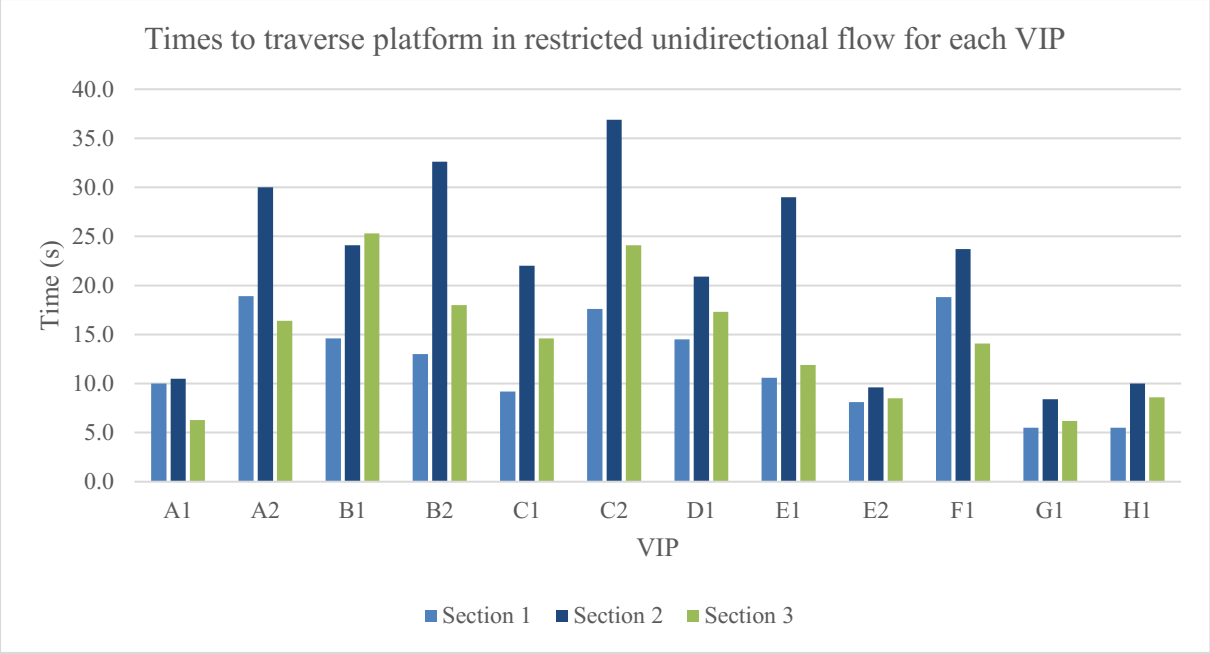


Figure 5.26: Times to traverse platform in restricted unidirectional flow for each VIP.

This is a significantly different performance than the unrestricted group flow, which yielded improvements in performance across all sections of the platform relative to the individual passes. Indeed, in comparing the restricted and unrestricted unidirectional flows, it is observed that the restricted condition increased mean time to traverse the platform by 1.7 s, 2.4 s, and 1.9 s for section 1, section 2, and section 3, respectively. This translated to negative impacts on the effective speed of each VIP traversing the platform in restricted unidirectional flows, as illustrated in Figure 5.27.

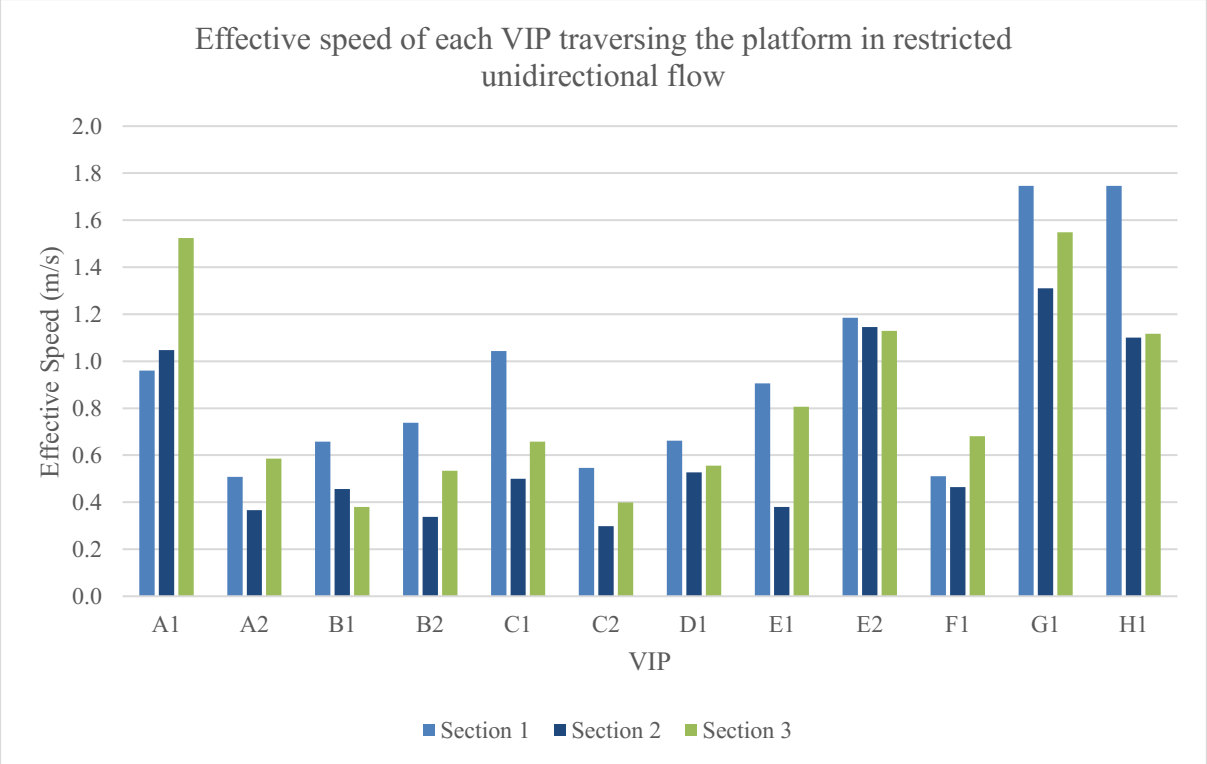


Figure 5.27: Effective speed of each NSP traversing the platform in a restricted unidirectional flow.

The mean effective walking speed of VIPs was 0.9 m/s for section 1 (SD = 0.4 m/s, CV = 46.7%), 0.7 m/s for section 2 (SD = 0.4 m/s, CV = 56.3%), and 0.8 m/s for section 3 (SD = 0.4 m/s, CV = 49.4%). Compared to the unrestricted condition, this was a broad decrease in mean effective speed by 0.2 m/s, 0.1 m/s, and 0.1 m/s for section 1, section 2, and section 3, respectively. As with individual and unrestricted unidirectional group performance, section 1 yielded the greatest effective walking speed relative to sections with obstacles. Moreover, section 2 continued to present a lower mean effective speed than section 3, suggesting that group performance tends to have the greater impact on environments with larger obstacles than those with steps or smaller ground-level obstacles.

While the spread of results remains broad regardless of the restricted or unrestricted condition (all presenting a CV above 40%), the restricted condition did slightly reduce the CV by 6.6% for section 1 and 6.0% for section 2, although the CV increased by 6.0% for section 3. These are considered to lie only slightly outside of margin of error. It can therefore be concluded that, although unidirectional group conditions can affect the spread of a sample's results, this is often insignificant. Different VIPs will continue to demonstrate a very broad performance dataset when compared to one another. It is therefore more useful to identify the individual progression and behaviours of a single VIP across multiple conditions than to compare a VIP's instantaneous performance to that of their sample. Such is demonstrated in Figure 5.28 where the percentage change between the times to traverse the platform individually and in restricted unidirectional flows for each VIP is calculated.

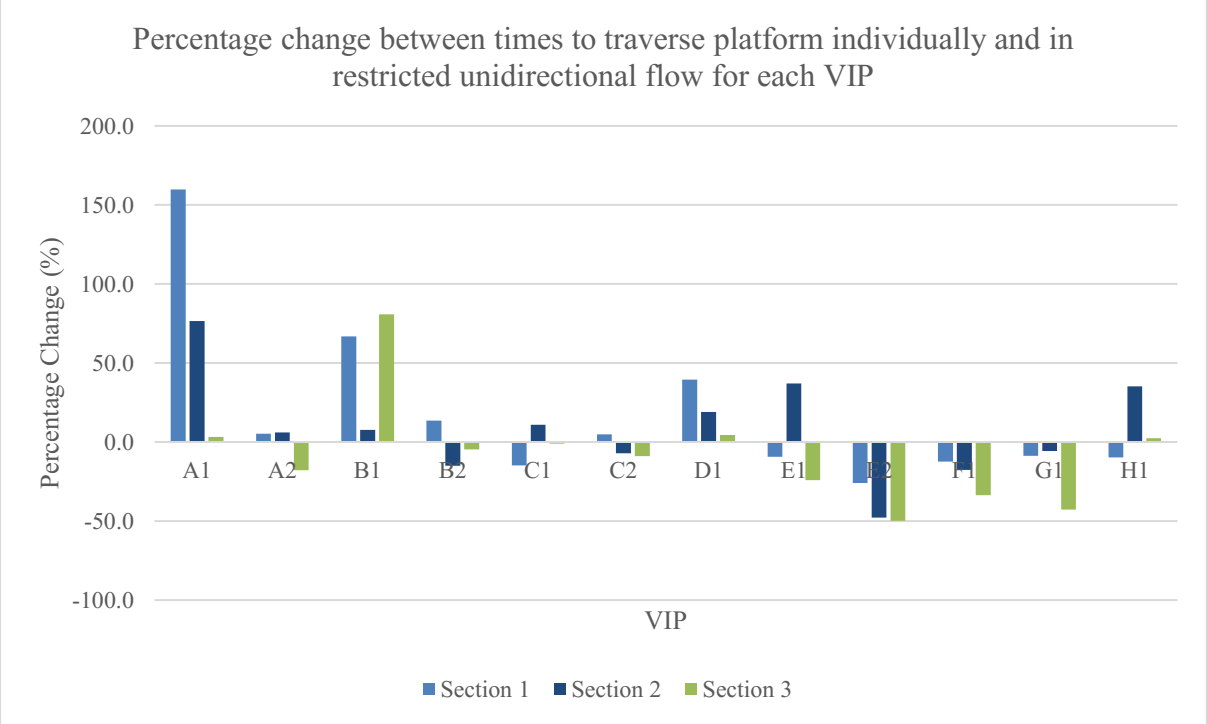


Figure 5.28: Percentage change between times to traverse platform individually and in restricted unidirectional flow for each VIP.

5 of 12 VIPs demonstrated an average increase in time to complete all 3 sections in a restricted unidirectional flow versus individual performance (2 more than in an unrestricted flow); these were A1, B1, D1, E1, and H1. Interestingly, both A1 and B1 had also required longer to complete a pass in the unrestricted flow, suggesting that these VIPs were particularly sensitive

to group conditions. Indeed, A1 and B1 experienced the greatest percentage increase in average pass time at 79.8% and 51.8%, respectively. This was followed by D1 and H1 at 21.0% and 9.2%, respectively. Lastly was E1 at 1.2% which is considered within margin of error. Once again, this could not be correlated with visual function as these VIPs belonged to Group 1, 2, 3, and 4 in considering visual impairment severity. However, this does suggest that severity of visual impairment is not a strong predictor of an individual's performance change between individual and group scenarios.

The magnitude of A1 and B1's performance change was significantly greater than the 18.8% maximum average percentage change recorded by B1 in the unrestricted flow. Contrarily, E2, F1, and G1 experienced 41.2%, 21.2%, and 19.1% reductions in mean time required to complete passes in restricted unidirectional flows than individually. The remainder of VIPs experienced, on average, insignificantly better performance than when operating individually; average percentage changes were less than 4% and not consistently across sections. For instance, A2 required more time to complete sections 1 and 2 in the restricted unidirectional flow versus individually, but less time in section 3. B2 required more time in section 1, but less time in section 2 and 3 (as was similarly observed in an unrestricted unidirectional flow). E1, F1, and G1 required less time to complete all sections versus individual performance.

While effective speed and its comparisons across scenarios are primary measures of performance, further investigation of the video footage, automated data, and questionnaire data indicate that group flows were smoother in restricted flows. These resulted in VIPs being, and feeling, safer and more comfortable. When asked to rank the five scenarios performed in the experiment (individual, unrestricted and restricted unidirectional, unrestricted and restricted opposing) from 1 (least comfort) to 5 (most comfort), the restricted unidirectional flow was ranked 0.2 points higher (receiving 4.0) than its unrestricted counterpart (receiving 3.8), on average. Both unidirectional flows were ranked higher than the individual flow (receiving 3.5).

From the video footage, it is apparent that the restricted condition led to the VIPs and NSPs passing as a group without the aggressive overtaking behaviour observed in the unrestricted unidirectional flow. As a result, the group typically moved at the speed of the slowest member and VIPs were therefore able to use NSPs for support. One such example is illustrated by Figure 5.29 where VIP C2 periodically touches their cane on the back of an NSPs' legs to orientate.



Figure 5.29: A VIP uses their cane to tap the NSP in front of them for orientation.

Another benefit to the flow structure within groups was that, while the group had a reduced overall time to traverse the platform relative to an unrestricted flow, the process of doing so was far less turbulent. Lane formations often occurred where participants maintained their position within the lane for the duration of the pass. This led to the VIP keeping a good orientation throughout the pass given that they were able to continuously couple with the

people around them through visual, auditory, or tactile means. VIP D1 explained that this allowed them to ‘follow people, keep with their speed, and slow down when they do and vice versa’. This was reflected in the lane-like performance achieved for all sections with D1 in a restricted unidirectional flow, as displayed in Figure 5.30.



Figure 5.30: Lane formation and a smooth group flow across all sections for a VIP in a restricted unidirectional flow.

The group better adapted to the width of each section in the restricted condition as each participant had greater time to rearrange themselves as the lanes within sections formed. For instance, the formation maintained in section 1 was two-wide at most. In section 2, this reduced to one-wide given the narrower pathways across openings. In section 3, this rose to a maximum of three-wide. Interestingly, even with multiple lanes, the coupling between VIP and NSP was very evident, as further exemplified by D1 in section 3.

In all other passes but the restricted unidirectional flow, this VIP’s cane collided with the foam block in section 3 as they attempted to traverse the section in a straight line, resulting in slight hesitation and walking instability. However, in the restricted unidirectional flow, D1 closely followed the NSP leading the group who then chose to manoeuvre around the foam blocks in an ‘S’ formation. The VIP therefore did not collide with the foam block. This phenomenon is described by Figure 5.31.



Figure 5.31: VIP visually coupling with an NSP to avoid a foam block.

D1 was registered as being SSI; while their visual function was insufficient to detect the ground-level obstacle, it was sufficient to couple with the leading NSP. The average pass time increased for all group members relative to individual performance; D1 required 21.0 s to complete this pass of section 3, a 4.5% change over their individual performance. The NSPs all yielded a similar walking path and performance to the VIP, resulting in a 208.8% increase in pass time relative to the individual NSP average of 6.8 s to traverse section 3.

The smoothness of this flow and the effect it had on the VIP's pass can be observed in Figure 5.32. The straight walking path across the section with the purposeful manoeuvre to avoid the foam block is visible in the coordinate plot. Moreover, the gradual increase and decrease of speed, with 0.7 m/s maintained throughout the centre of the pass, confirms that this was a stable and safe flow.

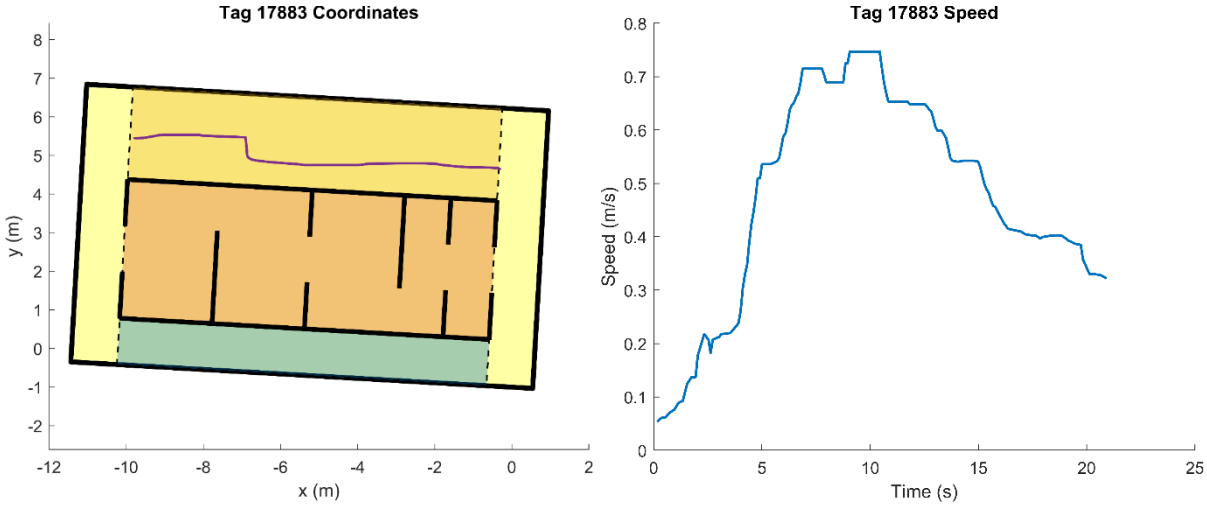


Figure 5.32: VIP operating in a restricted unidirectional flow in section 3.

This compromise in ultimate effective walking speed for elevated safety was beneficial in this instance. However, the significant decrease in effective walking performance for certain VIPs, particularly VIP A1, may suggest otherwise. Indeed, VIP A1 experienced a 79.8% average percentage increase in time required to complete passes in a restricted unidirectional flow versus their individual performance. This prevailed in section 1 where the percentage increase was 159.7%. As displayed in Figure 5.33, the restricted unidirectional pass within this section

was exceptionally smooth and controlled, with group members maintaining a two-abreast formation throughout the entirety of the pass.



Figure 5.33: VIP operating in a slower restricted unidirectional flow across section 1.

It is evident that A1 was a very fast-walking VIP, matching or exceeding the walking performance of the NSPs when operating individually. Moreover, A1 was registered as SI and was categorised into group 4 for retaining the best visual function of the VIP group. Therefore, in section 1, the group acted to slow down A1. This was unlike all other VIPs where the VIP was the slowest member of the group. Instead, the conventional relationship between decreasing speed and increasing density prevailed, and visual impairment no longer acted as the limiting factor in this group's collective performance. A1's poorer effective walking speed in section 1 was therefore a result of the elevated density caused by section 1's narrower width. This was improved in sections 2, and then improved again in section 3 as width increased and density decreased.

Table 5.9 summarises the findings from both the unrestricted and restricted unidirectional flows considering the average performance across sections to demonstrate the significance of environmental changes. Note that the percentage change here is found between the total average baseline and unrestricted/restricted unidirectional flow times to traverse each section, rather than averaging the individual percentage changes for VIPs, as previously calculated.

Section	Total Avg. Time to Traverse Each Section [s]			Change from Baseline [%]	
	Baseline	Unrestricted	Restricted	Unrestricted	Restricted
1	11.4	10.5	12.2	-7.9	7.0
2	21.4	19.1	21.5	-10.7	0.5
3	15.8	12.4	14.3	-21.5	-9.5
Avg.	16.2	14.0	16.0	-13.4	-0.7

Table 5.9: Average time to traverse platform in unidirectional group flows for all VIPs.

Simply, the introduction of both unidirectional group conditions did not yield an average decrease on VIP performance, as was hypothesised. Instead, unrestricted group flows yielded an average performance increase of 13.4% versus individual performance across all sections. The restricted condition reduced this to a moderate performance increase of 0.7% versus individual performance. The unrestricted condition led to typical reductions in all sections, with section 3 experiencing the largest performance benefit for both unrestricted and restricted flow conditions.

It is generally observed that the velocity of the VIP increased from baseline in all unidirectional group conditions. Certain VIPs almost matched NSP velocities, especially in unrestricted flows. However, whilst passes were generally quicker in unrestricted flows, the crowd behaviour was chaotic with several collisions and failed overtaking attempts. Moreover, on occasions where the VIP lost spatial orientation, a significant impact on group performance was observed and the VIP was left behind. Fewer such events of VIP disorientation occurred in restricted flows. When they did occur, the less turbulent nature of the crowd observed in the restricted flows provided sufficient time for reorientation. This allowed for unique VIP behaviours to become apparent, such as the VIP that used their cane to orientate by tapping the NSP they were following.

In summary, the significantly increased velocities in unrestricted flows relative to restricted flows accounted for the increased events of VIP disorientation. However, the turbulent nature of the crowd introduced safety concerns on VIPs with poor orientation and perceived comfort. The restricted unidirectional flow was therefore ranked as the most comfortable scenario, on average, by VIPs.

5.7. Opposing Group Flow

5.7.1. Unrestricted Opposing Group Flow

Opposing group behaviour and walking metrics are primarily observed from the video footage. Unlike the unidirectional flow, all VIPs and NSPs within each session were present on the platform throughout the opposing group flows, constituting either one of two groups that were positioned on opposing ends of each section. The maximum density on the platform therefore increased relative to all other scenarios at the points where the opposing groups met. This was hypothesised to be necessary to present the greatest range of group behaviours.

An unrestricted and restricted pass of each section was conducted and the time to traverse the platform for each VIP was found, as was the effective speed. The automated data collected was then utilised to further detail specific behaviours seen throughout the video footage. An insufficient number of NSPs was present to formulate an opposing flow for VIP H1. Instead, the experiment was varied to conduct two scenarios: one where a single NSP opposed a group including the VIP, and another where the VIP opposed the group of NSPs. The results of this variation are detailed and discussed in the next section. Subsequently, a new set of mean times, standard deviations, and coefficients of variation are calculated for the individual and unidirectional flows excluding H1 (available in the appendices). This ensures fairness of comparison between all scenarios.

All comparisons within this section therefore only consider these values. Figure 5.34 highlights the time to traverse the platform required by each VIP in an unrestricted opposing group flow. The mean time to traverse section 1 was 11.9 s (SD = 3.0 s, CV = 25.6%), section 2 was 19.9 s (SD = 8.0 s, CV = 39.9%), and section 3 was 12.8 s (SD = 3.7 s, CV = 29.3%). In comparing to the individual flows, this represented a mean increase of 0.1 s for section 1, a mean decrease of 2.8 s for section 2, and a mean decrease of 3.7 s for section 3.

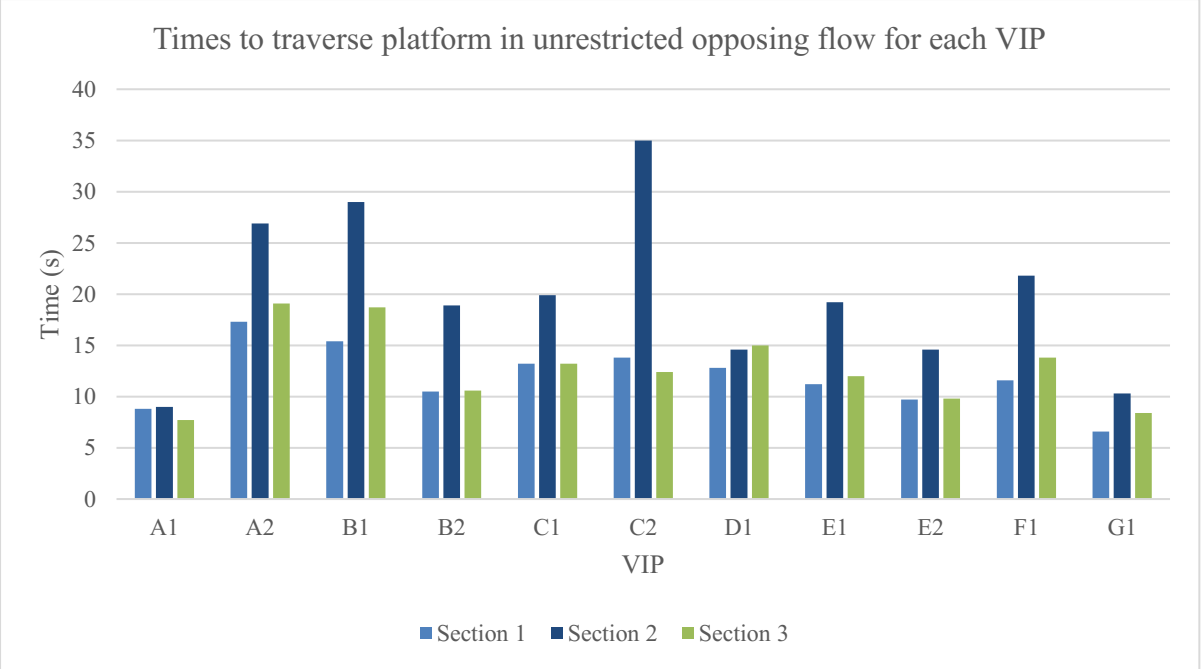


Figure 5.34: Times to traverse platform in unrestricted opposing flow for each VIP.

Figure 5.35 denotes the effective speed of VIPs traversing the platform in unrestricted opposing flows. The mean effective walking speed of VIPs was 0.9 m/s for section 1 (SD = 0.3 m/s, CV = 29.2%), 0.6 m/s for section 2 (SD = 0.3 m/s, CV = 44.0%), and 0.8 m/s for section 3 (SD = 0.2 m/s, CV = 29.5%). As in individual and unidirectional group performance, Section 1 remained the highest performing section when considering average effective time and speed. This was followed by section 3, and then section 2, as was similar in unidirectional flows, but dissimilar in individual performance where section 2 and section 3 presented identical effective speeds at 0.7 m/s.

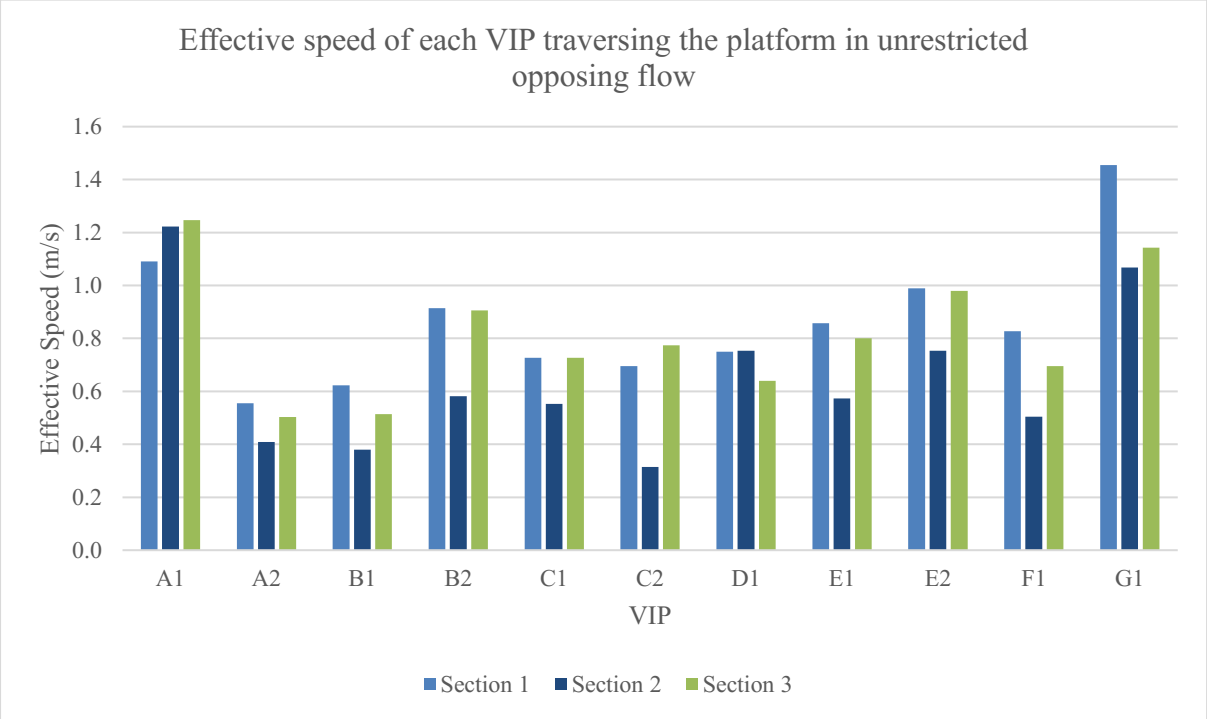


Figure 5.35: Effective speed of each NSP traversing the platform in an unrestricted opposing flow.

The mean decrease and increase in effective speed of 0.1 m/s for section 2 and section 3, respectively, lie within rounding error. Both sections experienced a mean decrease in mean time to traverse the platform in the opposing flow relative to individual performance. This is unexpected given that crowds, particularly in an opposing flow with higher density, should have had profound negative impacts on these VIPs. It appears that performance in an opposing flow is therefore dependant on the presence of larger and smaller obstacles, with optimal performance occurring in a straight section without obstacles.

Furthermore, the introduction of the opposing flow reduced the spread of results when compared to individual performance (the spread of time to traverse the platform is considered in this comparison). In section 1, the CV decreased by 18%, substantially more than the 6.9% decrease introduced in the unrestricted unidirectional flow. In section 2, the CV decreased by 7%, whereas the unrestricted unidirectional flow resulted in a 6.5% increase. In section 3, the CV decreased insignificantly by 3.3%, whereas an insignificant increase of 1.6% was found in the unrestricted unidirectional flow. The introduction of the opposing flow was expected to create the most chaotic environment and, presumably, the largest spread of results, yet the contrary prevailed when considering mean performance. A further investigation into each VIP's performance is necessary; Figure 5.36 displays the percentage change between times to traverse the platform individually and in unrestricted opposing flow for each VIP.

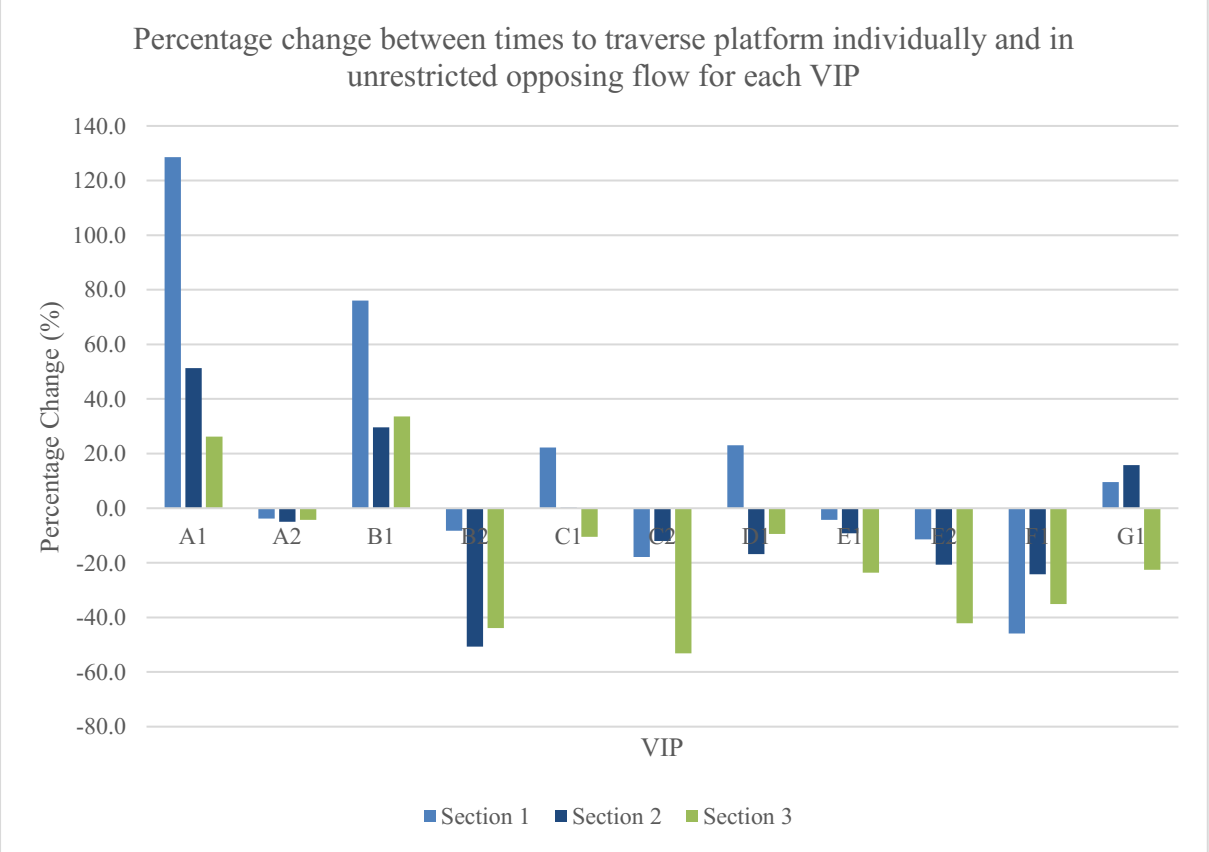


Figure 5.36: Percentage change between times to traverse platform individually and in unrestricted opposing flow for each VIP.

4 of 11 VIPs demonstrated an average increase in time to complete all 3 sections in an unrestricted opposing flow versus individual performance; these were A1, B1, C1, and G1 with average percentage changes of 68.7%, 46.4%, 4.0%, and 0.9%. A1 and B1 continued to

experience significantly worsened performance, reaffirming these VIPs' sensitivity to group conditions. Moreover, in comparing A1 and B1's performance in an unrestricted unidirectional flow, the unrestricted opposing flow led to a percentage change that was 5.5 times and 2.5 times greater in magnitude, respectively. The remainder of VIPs experienced, on average, better performance that was more consistent across sections, unlike prior scenarios. This is exemplified by A2, B2, C2, E1, E2, and F1 where less time was required to complete every section in the unrestricted opposing flow versus individually.

A likely explanation for the reduced performance in section 1 relative to baseline is the narrower width of section 1 than the other sections. This is similar for the unidirectional flows. Figure 5.37 illustrates the high densities that prevailed in this section as the opposing groups met, yielding a density of 3.7 persons/m^2. Moreover, this figure demonstrates the close-proximity lane formations that occurred in this type of flow. Here, participants would order themselves into lanes only upon touching distance of one another.



Figure 5.37: High density and close-proximity lane formation in section 1 during an unrestricted opposing flow.

The delay to queue resulted in participants coming to a complete stop until a decision was made on how to pass. This decision was either bilateral, where both opposing participants conjointly moved to their chosen position to avoid contact, or unilateral, where only one participant moved to a position to avoid contact. A primarily unilateral performance was observed when a VIP was leading their group, necessitating the opposing NSP to make the decision as to where and when to move, or to risk a collision. This was a turbulent process that could lead to hesitation and poor decision making by the opposing NSP. Such is exemplified in Figure 5.38 where an opposing NSP came to a complete stop as they met the opposing VIP (A2).



Figure 5.38: Unilateral decision and hesitation by an NSP causing a bottleneck, the opposing lane coming to a halt, and the other lane dominating and passing.

Here, this NSP (positioned at the bottom right of the first image), directly encountered the oncoming VIP. The NSP moved from left to right several times as they hesitated to decide their path forward while the VIP slowed down. This caused the group behind the VIP to stop, allowing the other group behind the NSP to dominate and pass the stopped group in a smooth lane. The NSP then made the ineffective decision of moving further to the right to create a new lane for themselves against a wall, rather than following their group's lane. The group behind the VIP had to then shift position to avoid contact with the oncoming NSP.

This explains A1's substantially increased time to complete section 1, while A2, the VIP in the above altercation, still managed to finish ahead of their individual performance. As seen in the unidirectional flows, this affirms that VIPs such as A1 with better visual function behave more closely to NSPs: they experience performance reductions induced by the group rather than their ability to detect the environment around them.

Figure 5.39 presents the coordinate plot and speed of A2 as they encountered the NSP. It can be seen that A2's path was almost perfectly efficient, but that the delay in completing the pass was a result of the sudden dip in speed occurring as they interacted with the oncoming NSP between 6 and 10 s into the pass. This dip momentarily reached 0 m/s, although the smoothing applied to the data for visual clarity compromised this. While the effective speed suggests that this was a faster (and better) pass than individual performance, the stop-start behaviour exemplifies the undesirable characteristics of an opposing flow.

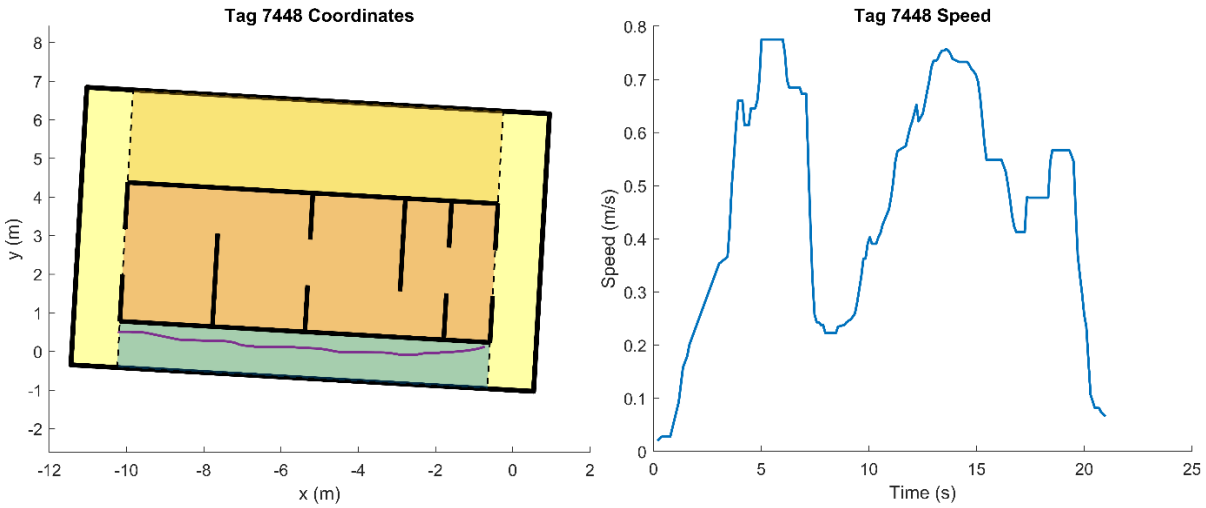


Figure 5.39: VIP stopping and starting on encountering an oncoming NSP that hesitated when making a unilateral decision.

In addition to the VIP's impact on the closest incoming NSP, other NSPs in both opposing groups would actively avoid the VIP. These NSPs often changed their direction and formed lanes around the path taken by the VIP. The VIP therefore dominated the flow and would determine the successfulness of the pass, also shown in the prior example (Figure 5.38 and 5.39). Here, all NSPs behind the VIP exhibited identical performance to the VIP as they formed a lane behind the VIP. Similarly, in Figure 5.40, the NSPs unilaterally avoided the group with the oncoming VIP, shifting directions while the group behind the VIP followed the VIP to avoid collision with them. As this occurred in section 3, a section wider than section 1, the two groups passed without the abrupt stop-start behaviour observed in the prior example.

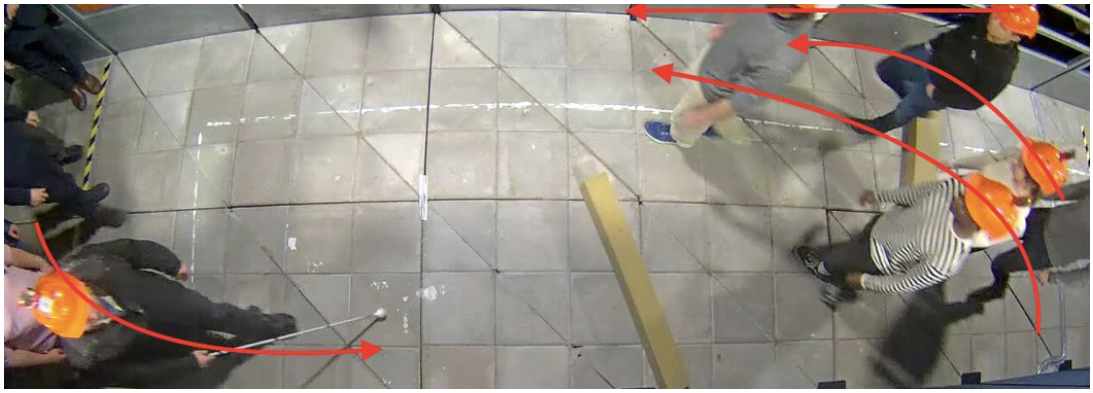


Figure 5.40: VIP dominating the flow and pressuring a lane formation.

In narrower environments, a 'deadlock' scenario could occur, as in section 2 of session C's unrestricted and restricted opposing flows. Figure 5.41 describes this phenomenon. Here, the group behind C2 (positioned at the top of the image), managed to overtake C2 as they collided into a wall (their cane protruding through the opening in the leftmost image). Contrastingly, the group behind C1 remained dominated by C1 without overtaking opportunity. C2's group left C2 behind, as they did in the unrestricted unidirectional flow. C2's group therefore gained significant momentum over C1's group which was met much further down the platform. A deadlock was formed, and C1's group was pushed back as C2's group prevailed and completed the pass.

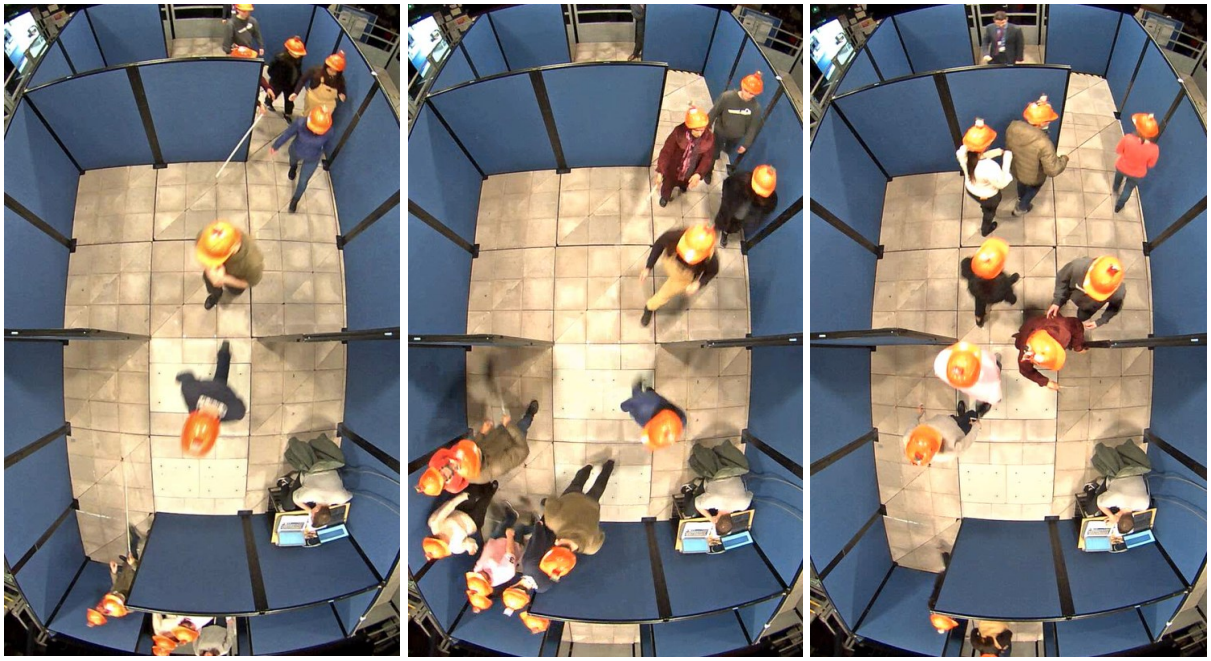


Figure 5.41: Deadlock formation in an unrestricted opposing flow where one opposing group gains momentum over the other.

Consequently, all but one NSP within C2's group completed the pass prior to anyone in C1's group. C1's pass time was minimally affected by this phenomenon compared to their individual pass, while C2 experienced a 12% reduction in pass time. This was a result of the single NSP that remained behind C2, guiding them until the end of the pass. Contrarily, C2 dominated this NSP's performance. Figure 5.42 plots the coordinates of an NSP behind C1 (left) and an NSP that overtook C2 (right). The NSP behind C1 moved from right to left on the plot, while C2 moved from the left to right.

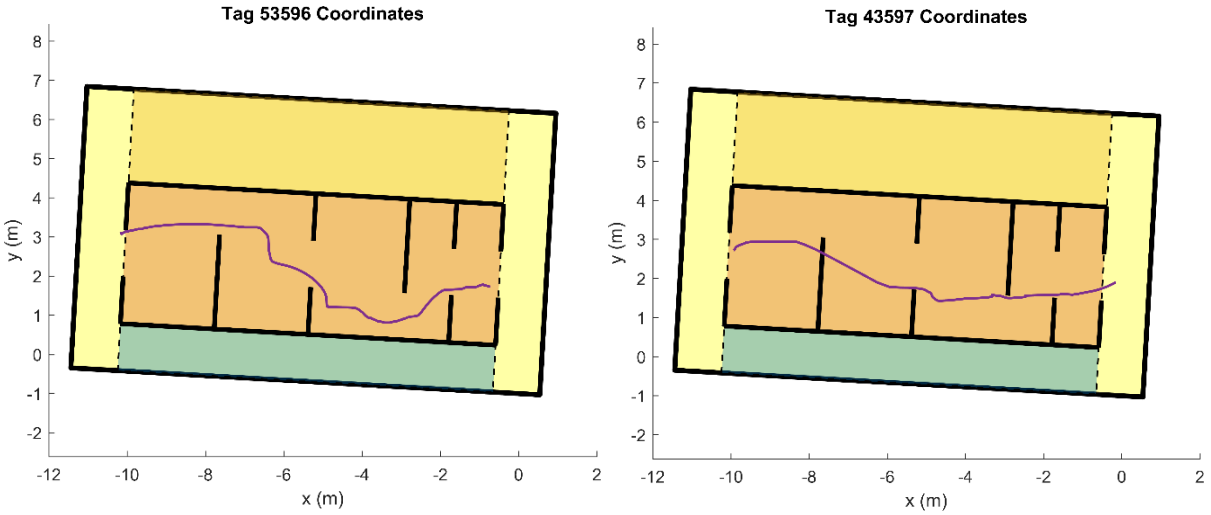


Figure 5.42: Coordinate plots of an NSP behind C1 (left) and an NSP that overtook C2 (right).

It can immediately be observed that the NSP behind C1 had a less efficient path. This resulted from being pushed to the bottom wall when the opposing group used their momentum to complete the pass (between x = -6 m and x = -2 m). Contrastingly, the NSP that overtook C2 had a very efficient pass that was approximately 1.5 metres shorter than the former. Figure 5.43 graphs the speeds of the NSP behind C1 (left) and the NSP that overtook C2 (right).

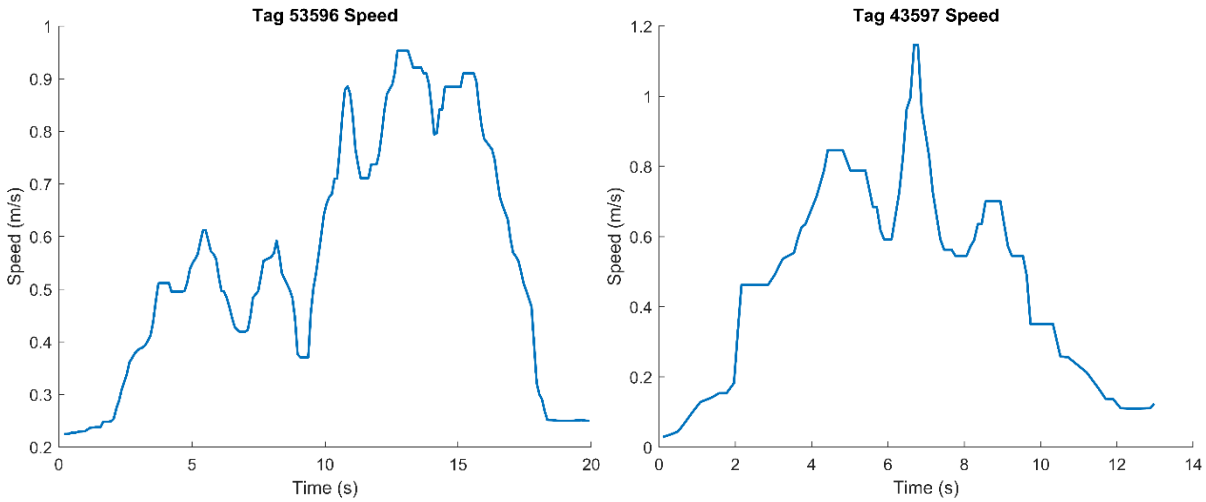


Figure 5.43: Speed of an NSP behind C1 (left) and an NSP that overtook C2 (right).

The NSP behind C1 required 20 s to complete the pass, 7 seconds slower than the VIP that overtook C2. This translated to their respective average speeds of 0.58 m/s and 0.76 m/s. Moreover, the speed profiles are telling of which NSP was in the dominating group. Specifically, the NSP behind C1 had a slow start, taking 4 s to accelerate to 0.5 m/s, followed by sudden dips and peaks between 0.4 m/s and 0.6 m/s as the opposing group pushed past. Only then could this NSP accelerate to 1 m/s before completing the pass. Contrarily, the NSP that overtook C2 had their performance dominated by C2 for 2 seconds where they overtook on the inside wall, brushing it while accelerating to over 1 m/s before experiencing a lesser dip and peak as they encountered the slower opposing group and completed the pass.

The unrestricted nature of the flow limited the time available for group members to perform these manoeuvres, resulting in collisions when they failed to do so. This is presented in Figure 5.44 where a collision occurred when a lane was not formed in sufficient time. Here, VIP F1 initially moved alongside an NSP within their group. However, the opposing group approached F1 as their cane was swiping in the opposite direction, missing the incoming NSP given the fast-moving flow. F1 therefore collided with the incoming NSP, pushing them against the wall while the other NSPs braced for impact. Note the extension of the NSP's arm to maintain balance and prevent further collision with the group behind F1. Ultimately, F1 was physically moved into the opposing wall, re-joining their group's now-single lane formation.



Figure 5.44: Collision occurring in an unrestricted flow resulting from delayed lane formation.

In this instance, F1 continued to complete the pass 45.9% faster than their individual pass. In comparing the video footage, it is evident that F1 increased their walking speed throughout the entirety of the pass from continuous crowd forces. Subsequently, their performance was similar to the other NSPs within the group, excluding the instantaneous sharp collision with the opposing NSP. From these examples, it is apparent that an unrestricted opposing flow can significantly increase VIPs' effective speeds through similar mechanisms as those in unrestricted unidirectional flows. However, the risk of poor decision making, delayed lane formation, deadlocking, and collisions result in unrestricted opposing flows presenting the most hazardous environment for all group members. This translated to VIPs' comfort, as can be observed in Figure 5.45 where the mean effective speed for each section versus mean comfort score for VIPs is plotted for the unrestricted opposing flow.

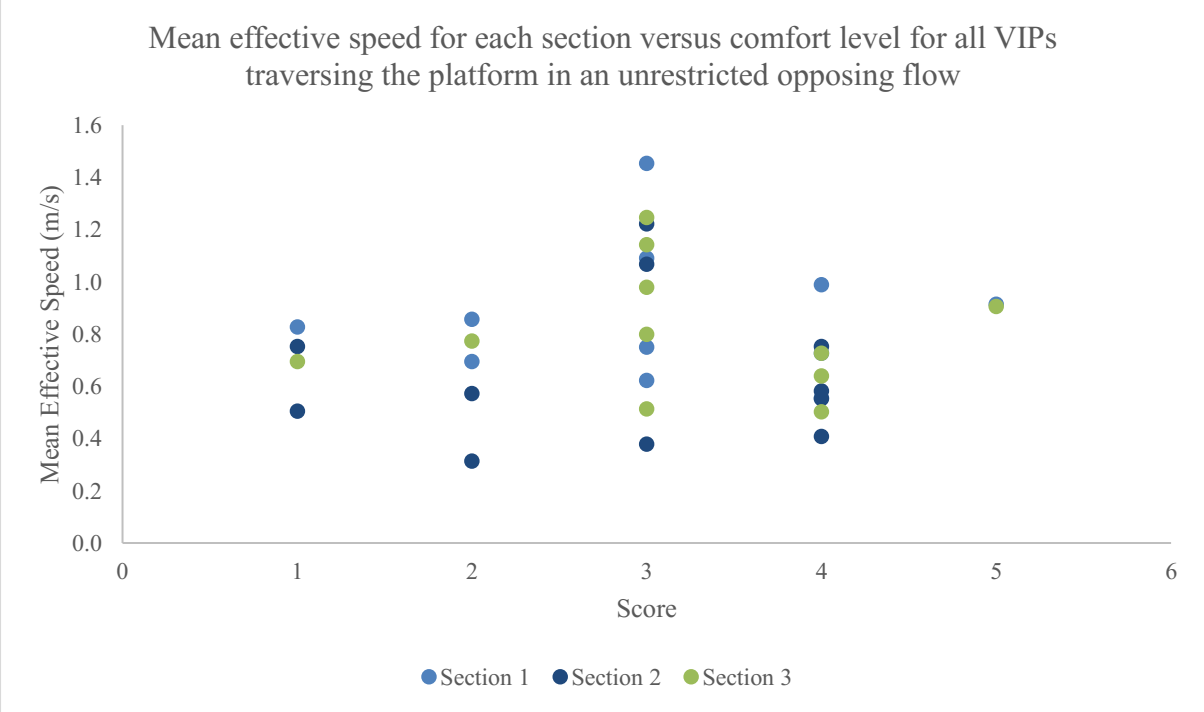


Figure 5.45: Mean effective speed for each section versus comfort score for all VIPs traversing the platform in an unrestricted opposing flow.

There appears to be no correlation between comfort and walking speed for the unrestricted opposing flows. This is unlike both the individual and unidirectional scenarios that presented an overall positive correlation between confidence and effective walking speed in all sections. Moreover, there existed four scores of 1, and only two scores of 5, with 3 being the modal score. This contrasts with the unrestricted unidirectional flows where only two scores of one were recorded. Additionally, more participants scored above 3 in unrestricted unidirectional flows than opposing flows. Interestingly, the largest spread of effective speeds was recorded at a score of 3 in the unrestricted opposing flow, rather than a score of 5 in the individual and unidirectional scenarios. Participants with the highest effective speeds that would correspondingly score higher in the individual and unidirectional scenarios therefore scored lower in the opposing flow.

Unlike all other scenarios, section 3 presented the highest mean score of 3.2 (SD = 1.1, CV = 33.9%), followed by section 1 at 3.1 (SD = 1.1, CV = 36.8%), and section 2 at 2.8 (SD = 1.2, CV = 41.4%). All three mean scores lie significantly below those of the unrestricted unidirectional scenario, which yielded scores of 3.9, 3.7, and 3.8 for sections 1, 2, and 3, respectively. Moreover, the minimum CV in the unrestricted opposing scenario was 4.6% greater than the maximum CV for the unrestricted unidirectional scenario.

Section 3's higher score is likely a result of the wider platform width where less turbulent behaviour is observed than the other sections. This suggests that the presence of ground-level obstacles was no longer the limiting factor in this section's performance, but rather its capacity to accommodate the higher densities within the opposing flows. In conjunction with the overall lower and wider spread of scores, it can be concluded that the opposing scenario was the least desirable scenario for VIPs. This overshadowed the increase in some VIPs' effective performance. Figure 5.46 displays the relationship between the mean effective speed versus mean effective comfort score for each VIP in an unrestricted opposing flow.

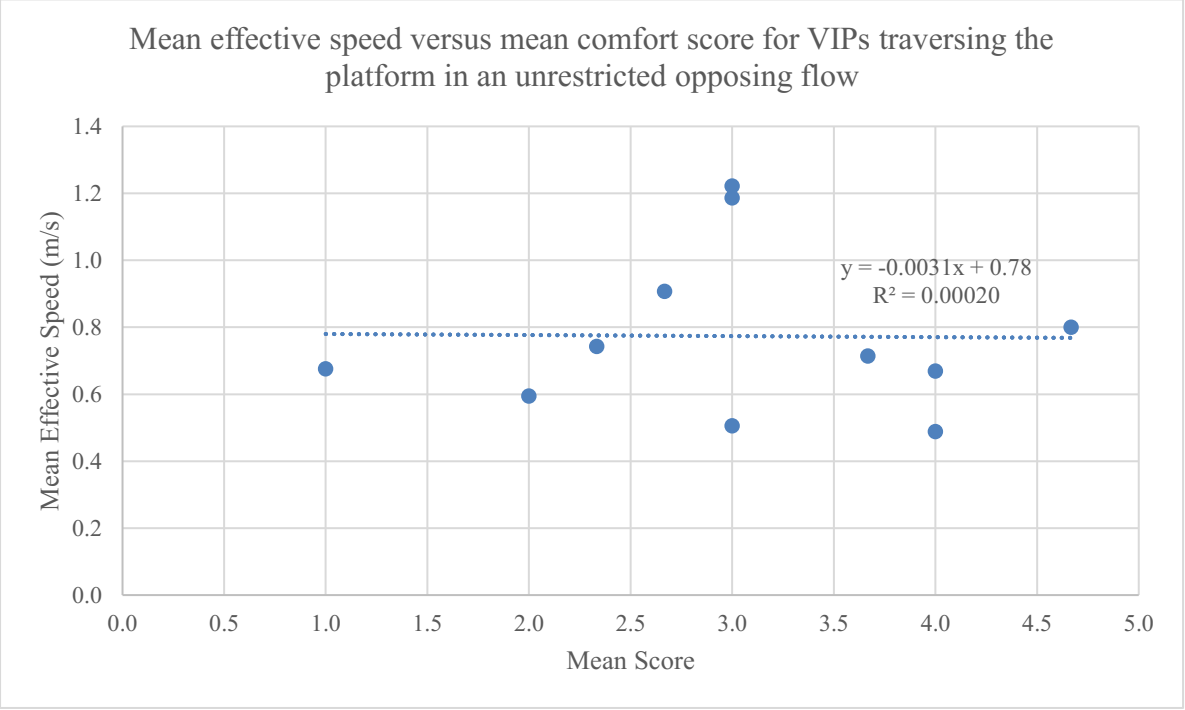


Figure 5.46: Mean effective speed versus mean comfort score for VIPs traversing the platform in an unrestricted opposing flow.

The line of best fit for mean effective speed against mean score is determined to have equation:

$$\overline{v_0} = -0.0031\bar{S} + 0.78$$

Where $\overline{v_0}$ is the mean effective individual walking speed, and $\bar{S}$ is the mean comfort score. This result is presented with a coefficient of determination (R^2) of 0.00020, suggesting no correlation between mean score and mean effective walking speed for VIPs operating in unrestricted opposing flows. The introduction of opposing group flows destabilises the VIP's control of their physiological and psychological performance, much more so than the unidirectional scenario. Contrastingly, in individual performance, there was a strong correlation between effective speed and mean score. This suggests that VIPs controlled their speed according to their psychological state.

5.7.2. Restricted Opposing Group Flow

As in the case of the unrestricted opposing group flow, all comparisons within this section only consider values excluding H1's prior performance. Figure 5.47 displays the time to traverse the platform required by each VIP in a restricted opposing group flow. The mean time to traverse section 1 was 13.7 s (SD = 4.1 s, CV = 29.6%), section 2 was 21.9 s (SD = 6.2 s, CV = 28.3%), and section 3 was 15.0 s (SD = 5.2 s, CV = 34.5%). Compared to the unrestricted opposing flows, this represented an increase of 1.8 s, 2.0 s, and 2.2 s, for section 1, section 2, and section 3, respectively.

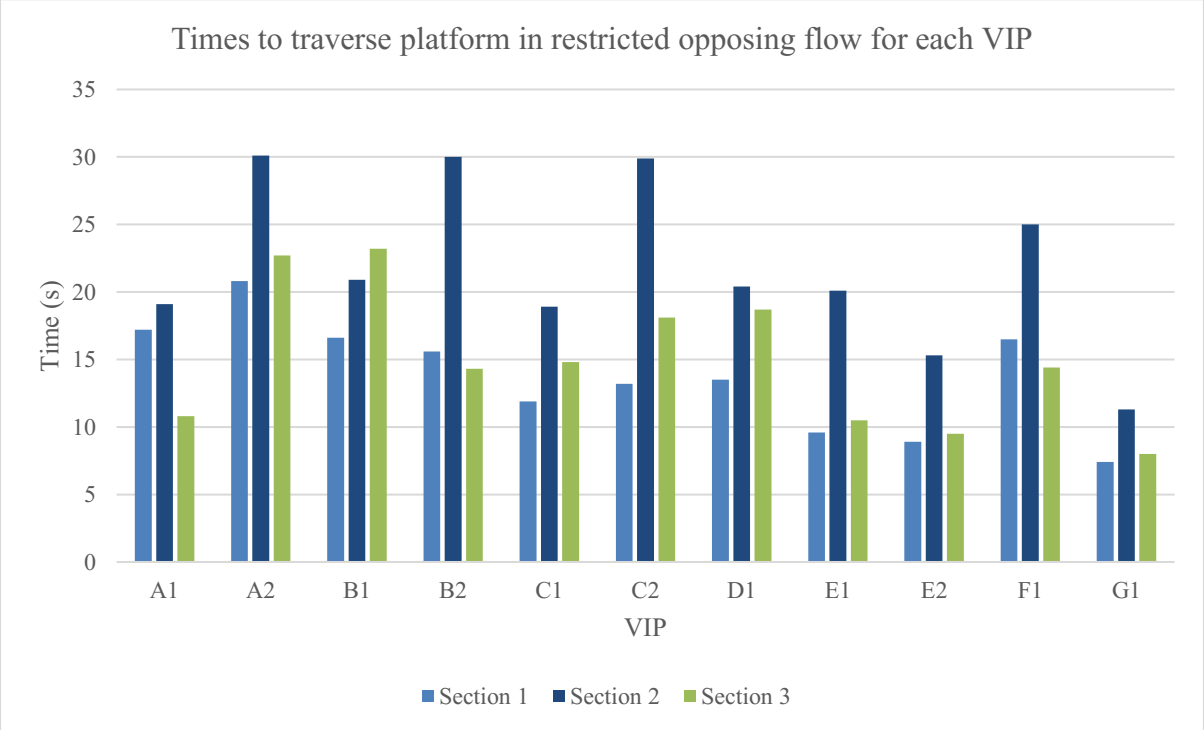


Figure 5.47: Times to traverse platform in restricted opposing flow for each VIP.

VIPs' effective speeds when traversing the platform in restricted opposing flows is presented in Figure 5.48. The mean effective walking speed of VIPs was 0.8 m/s for section 1 (SD = 0.3 m/s, CV = 33.8%), 0.5 m/s for section 2 (SD = 0.2 m/s, CV = 32.9%), and 0.7 m/s for section 3 (SD = 0.3 m/s, CV = 35.6%). This represented a slight but consistent decrease of 0.1 m/s in effective walking speed across all sections relative to the unrestricted opposing scenario.

Subsequently, section 1 remained the best-performing section when considering effective time and speed, followed by section 3, and then section 2, as was similar in unidirectional flows.

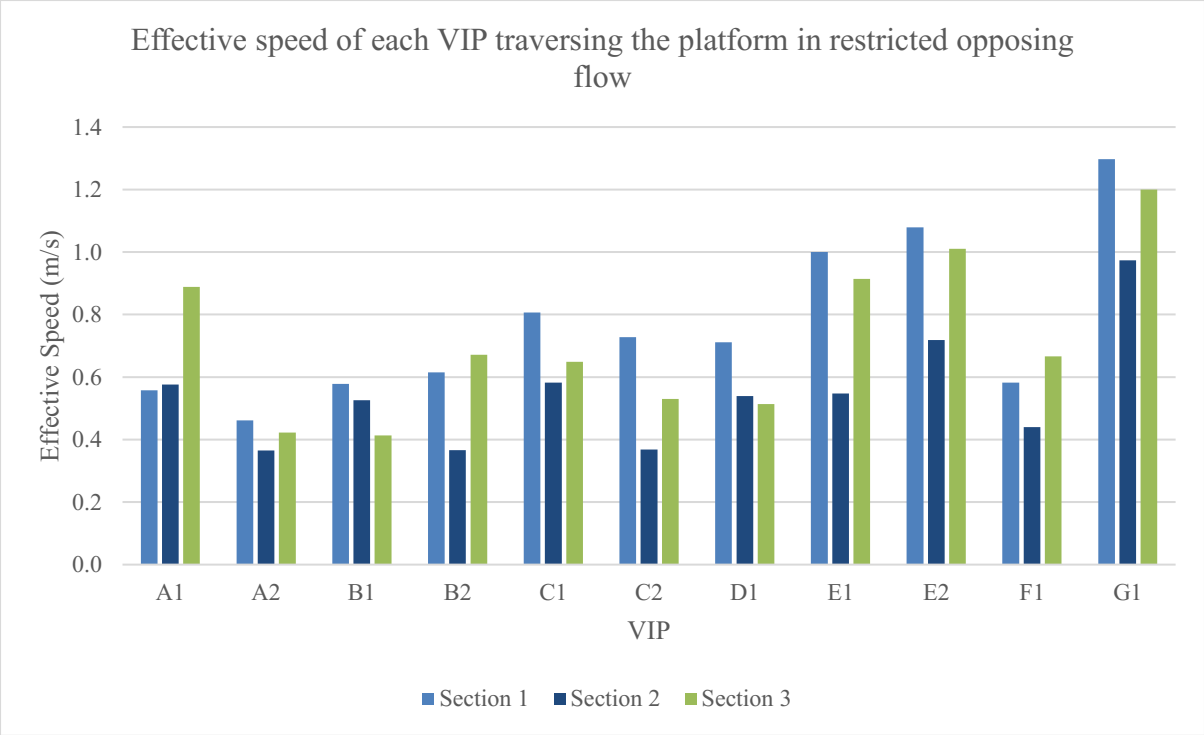


Figure 5.48: Effective speed of each NSP traversing the platform in a restricted opposing flow.

A very similar occurrence was observed on introducing the restricted condition to an unrestricted unidirectional flow. Here, a broad and consistent decrease in performance is observed (although section 1 experienced a more significant 0.2 m/s mean effective speed decrease in the unidirectional scenario). Furthermore, the continued slight discrepancy between section 2 and 3's performance in the restricted opposing flow suggests that larger and smaller obstacles had different impacts on a VIP's effective speed. Optimal performance occurred in a straight section without obstacles.

The restricted opposing flow had a smaller spread of results when compared to the individual scenario, but not to the unrestricted opposing scenario (the spread of time to traverse the platform has been considered in this comparison). Relative to the unrestricted condition in section 1, the CV increased by 4.6%. In section 2, the CV decreased by 11.1%. In section 3, the CV increased by 6.1%. These are relatively minor variations given the significant spread of results observed in all scenarios, and the conclusion that group scenarios do not necessitate a reduction from a VIP's individual effective performance remains true for a restricted opposing flow. However, as with all scenario variations, a further investigation into each VIP's pass demonstrates that each experienced different performance changes. Figure 5.49 displays the percentage change between times to traverse the platform individually and in restricted opposing flow for each VIP.

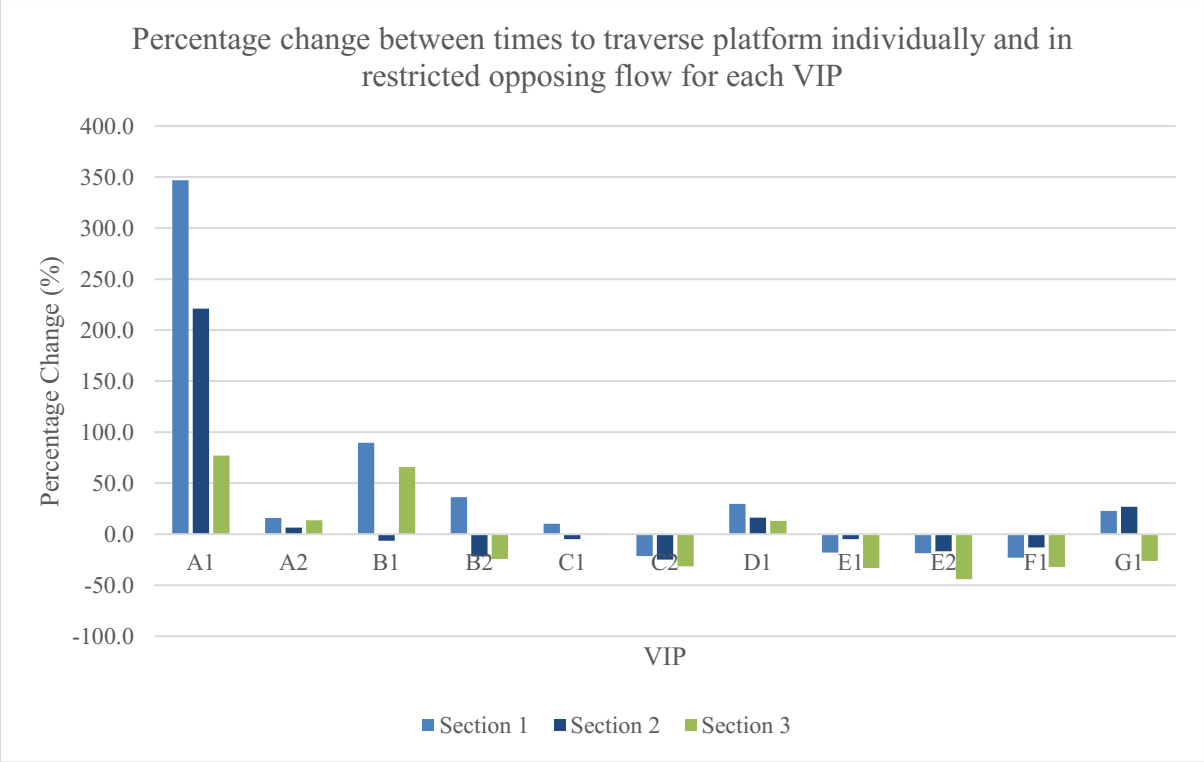


Figure 5.49: Percentage change between times to traverse platform individually and in restricted opposing flow for each VIP.

6 of 11 VIPs, the highest proportion of all scenarios, demonstrated an average increase in time to complete all 3 sections in a restricted opposing flow versus individually. These were A1, A2, B1, C1, D1, and G1 with average percentage changes of 214.9%, 12.0%, 49.6%, 1.9%, 19.7%, and 7.8%, respectively. A1 and B1 continued to experience significantly worsened performance, reaffirming these VIPs' sensitivity to group conditions. A1, in particular, registered their highest percentage change relative to all other scenarios with one that was 3.1 times that of the unrestricted opposing flow. Moreover, compared to the unrestricted opposing flow, 2 fewer VIPs registered performance gains in all sections. These were C2, E1, E2, and F1 (who also registered performance gains in all sections in the unrestricted opposing flow). Overall, the unrestricted condition continued to outperform the restricted condition when considering average percentage change for each VIP in group versus individual performance. In this instance, VIPs required 19% more time to complete all sections, versus 1.8% less time to complete all sections in the unrestricted opposing flow.

In similar fashion to restricted unidirectional flows, the restricted opposing flows led to more organised and durable formations within each opposing group as they initiated each pass. Figure 5.50 exemplifies two prevalent formations: a side-by-side pair formation, typically observed in section 1 and section 2, and a 'line-abreast' formation (Moussaid et al., 2010) typically observed in section 3. Indeed, these formations were dependant on section width, and were also held for as long as possible prior to the meeting and interaction of the two groups. Principally, the behaviours of the opposing groups prior to interaction could therefore be considered as separate, with each group operating as a restricted or unrestricted unidirectional flow depending on the stated opposing pass condition.



Figure 5.50: Side-by-side pair formation (left) and line-abreast formation (right) in a restricted opposing flow in sections 1 and 3, respectively.

Although more organised, restricted opposing interactions continued to present instances of turbulence and dangerous behaviour. These prevailed when there appeared to be sufficient time and space to pass without collision. For instance, in Figure 5.51, VIP C1 traversed through the centre of section 3, requiring the oncoming group to bifurcate. This caused the NSPs on either end of the VIP to funnel behind the VIP into a narrower lane. Soft collisions across the edges of this funnelling central lane occurred as the oncoming group traversed around it.



Figure 5.51: VIP bifurcating oncoming group into two lanes.

Collisions continued to occur in section 2 as well. Figure 5.52 presents examples from session B (left) and C (right). The example from session B is similar to that from Figure 5.51 where the NSP had to make a unilateral decision to avoid the incoming VIP and surrounding NSPs. This resulted in flow bifurcation, the NSP becoming wedged against the wall, and then pushing through the oncoming flow on the left-hand side. The NSPs behind them created a lane formation to the right-hand side, an identical behaviour to that observed in Figure 5.38 in section 1 of an unrestricted opposing flow.



Figure 5.52: Collisions occurring when a lane was not formed in sufficient time in a restricted opposing flow.

The example from session C highlights a collision between two opposing VIPs (C1 and C2) where neither could decide on their path forward given their severely reduced visual function. This induced a deadlock at a bottleneck, as described in Helbing et al. (2002). However, it was less severe than that occurring in the unrestricted flow as it occurred in the middle of the section. The NSPs behind each VIP had to then nudge the VIPs apart physically and into two separate lanes. Once again, the VIPs dominated the flow as each opposing NSP group followed closely behind. A smooth 'river-like' lane formation proceeded as shown in Figure 5.53 and described in Moussaid et al. (2010). Therefore, while the collision of the VIPs was fundamentally unsafe, their correction and the proceeding slow-down of the NSPs behind them resulted in a safer pass than the example from session B.



Figure 5.53: Lane formation following the collision, correction, and flow domination of two VIPs in a restricted opposing flow.

Figure 5.54 displays the coordinate and speed plot for VIP C2. The path on the coordinate plot moves from right to left. The path walked by C2 was very efficient, steered by the group forces from the opposing flow and resulting in a walking path of 11.0 m. This was a VIP that typically used the environment around them to orientate, resulting in an inefficient path and them being left behind in all unrestricted passes. The impact of the deadlock can be seen on the speed plot 15 s (halfway) into the pass where C2's speed suddenly dips to below 0.1 m/s. This then recovers to a steady 0.6 m/s as the group remained with C2 in a unidirectional formation. NSPs from both groups displayed similar performance, a markedly different outcome to the unrestricted opposing pass where one opposing group gained momentum over the other.

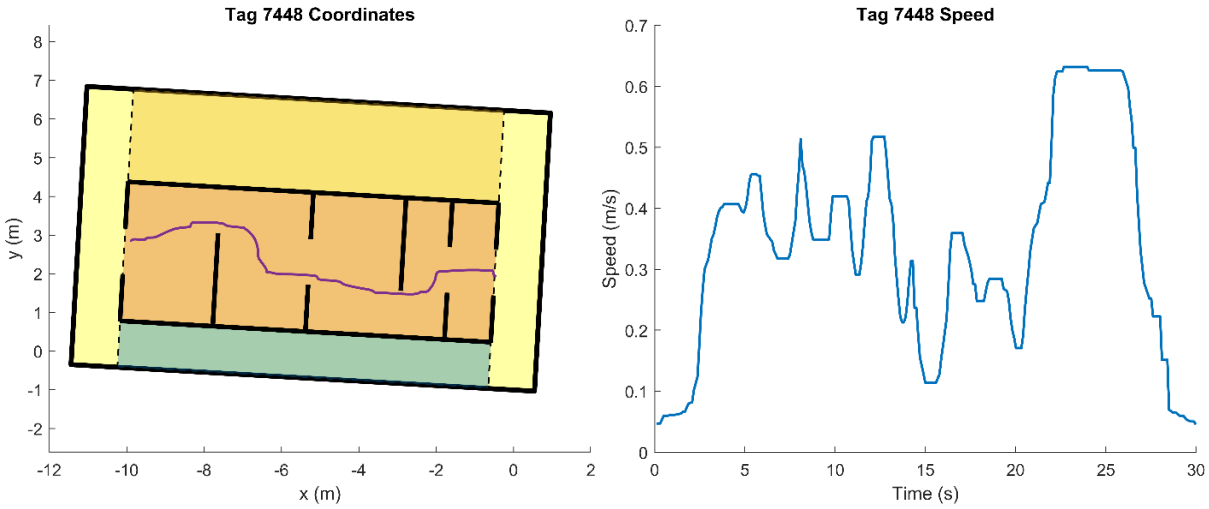


Figure 5.54: Coordinate and speed plot of a VIP coming to a deadlock and recovering in section 2 of a restricted opposing flow.

Finally, this improved organisation (while generally safer) resulted in substantially reduced effective performance in session A's pass. Particularly, this resulted in A1 recording a result 346.8% that of their individual pass, driven by their groups' maintenance of a side-by-side formation for an ineffectively long duration (Figure 5.55). Here, A2 traversed along the middle of the section, exacerbating the need for both groups to change formation to pass each other. Failing to do so led to the collision of the group leaders. The resulting delay of both groups was sufficiently long to allow the NSP time to turn around to look for the remainder of their group, shown in the rightmost image.



Figure 5.55: Excessive maintenance of group formation resulting in an inefficient pass in a restricted opposing flow.

Figure 5.56 presents the coordinate and speed plot of A1 as they traversed the restricted opposing flow in section 1. The path in the coordinate plot moves from left to right. The sharp right-angle turn at x = -6 m represents the point to which the group held their side-by-side formation, requiring A2 to suddenly merge and move against the wall to allow the opposing group to pass through. Note that this occurred in the approximate centre of section 1, creating a temporary deadlock where neither group had a momentum advantage, similarly to session C's restricted opposing flow in section 2.

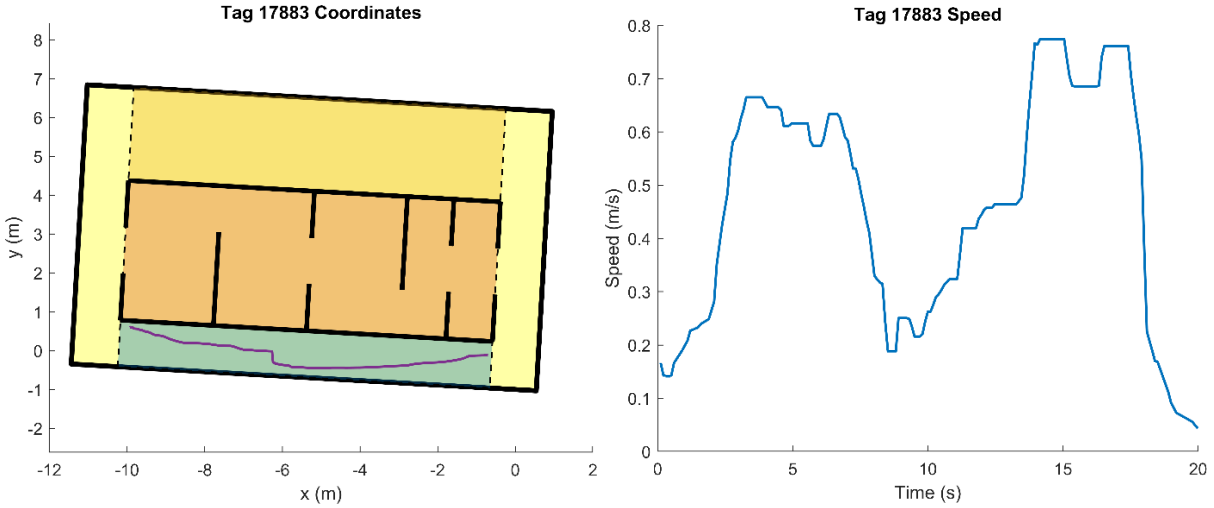


Figure 5.56: Coordinate and speed plot of a fast-moving VIP experiencing significant performance reduction in section 1 of a restricted opposing flow.

The speed plot visualises a smooth and well-maintained acceleration to 0.7 m/s prior to the sudden dip to below 0.2 m/s as the opposing groups met. This is followed by a recovery to 0.8 m/s to end the pass. The performance prior to and after the interaction of the groups is akin to that of a restricted unidirectional flow; the interaction of the groups continued to have the primary impact on effective speed regardless of whether the opposing flow was restricted or unrestricted.

Table 5.10 summarises the findings from both the unrestricted and restricted opposing flows considering the average performance across sections to demonstrate the significance of

environmental changes. VIP H1 has been excluded from all calculations, including at baseline. Note that the percentage change here is found between the total average baseline and unrestricted/restricted opposing flow times to traverse each section, rather than averaging the individual percentage changes for VIPs, as previously calculated.

Section	Total Avg. Time to Traverse Each Section [s]			Change from Baseline [%]	
	Baseline	Unrestricted	Restricted	Unrestricted	Restricted
1	11.8	11.9	13.7	0.8	16.1
2	22.7	19.9	21.9	-12.3	-3.5
3	16.5	12.8	15.0	-22.4	-9.1
Avg.	17.0	14.9	16.9	-11.3	1.2

Table 5.10: Average time to traverse platform in opposing group flows for all VIPs.

The introduction of the unrestricted opposing group flow yielded an average performance increase of 11.3% from individual performance, a marginally smaller change than the 13.4% increase introduced by the unrestricted unidirectional scenario. The restricted opposing flow was the first group scenario to yield a decrease from individual performance, albeit one that is small at 1.2%. Comparatively, the restricted unidirectional flow resulted in a moderate performance increase of 0.7% versus individual performance. The restricted condition, on average, was therefore slower than the unrestricted condition in unidirectional and opposing flows, with performance similar to that of the VIP acting individually.

Interestingly, section 3 experienced the largest performance benefit for both unrestricted and restricted flow conditions, while section 1 saw a performance detriment in both conditions. Given the higher density and prevalence of deadlock situations, this was primarily a result of the sections' differing widths, where section 3 was wider than section 1. Consequently, VIPs and NSPs presented converging performance, particularly in the restricted opposing flow where VIPs had the greatest dominance over the flow. In summary, all group conditions typically improved VIP performance at the cost of NSP performance, and this was most consistent in the restricted condition where the VIP dominated the entirety of the pass, rather than being overtaken during the pass.

In similar fashion to the unidirectional flows, whether an opposing flow was restricted or unrestricted influenced the safety of the pass with impacts beyond effective performance. Indeed, this primarily impacted opposing groups prior to their interaction where each acted unidirectionally. The restricted pass led to consistent group formations with VIPs following more efficient paths as group members remained with them at the cost of overall effective performance. Contrarily, the unrestricted pass resulted in VIPs being left behind with erratic overtaking behaviour and collisions.

Regardless of the restricted condition, all opposing flows presented dangerous behaviours on the interaction of opposing groups, including poor unilateral decision-making, collisions, deadlocking, stop-start waves, and lane bifurcation. In unrestricted passes, the group that gained momentum pushed the opposing group backwards, leading to aggressive collisions and deadlocking. In the restricted condition, deadlocking occurred centrally within each section. This was a consequence of longer formation durations and poor unilateral decision making, even when given more space and time than in unrestricted passes.

In summary, unrestricted group conditions continue to improve on VIPs' effective individual performance, on average. This prevails even in sections with obstacles and unfavourable opposing flows. However, such comes at the cost of safety and loss of group control, especially had the behaviours observed within this experiment translated to realistic high-risk environments. This remains true in restricted opposing flows, but not in restricted unidirectional flows where benefits to effective performance did not significantly compromise safety. VIPs' average ranking of both opposing flow conditions as the worst of all scenarios confirms this conclusion, particularly as the unrestricted opposing flow was the worst-ranked scenario.

5.8. Summary of Performance in all Scenarios

5.8.1. Summary Across Sections

Figure 5.57 displays the average effective speed for all VIPs (excluding H1 for fair comparison) when traversing the platform in individual, unidirectional, and opposing flows. Considering the section average for each scenario, the VIP effective speeds remain very consistent with only minor variation (within 0.2 m/s). In order of descending speed, the highest average effective speed of 0.9 m/s was presented by the unrestricted unidirectional flow. This was followed by individual performance, restricted unidirectional, and unrestricted opposing flows at 0.8 m/s. Finally, the restricted opposing flow yielded the lowest average effective speed across sections of 0.7 m/s.

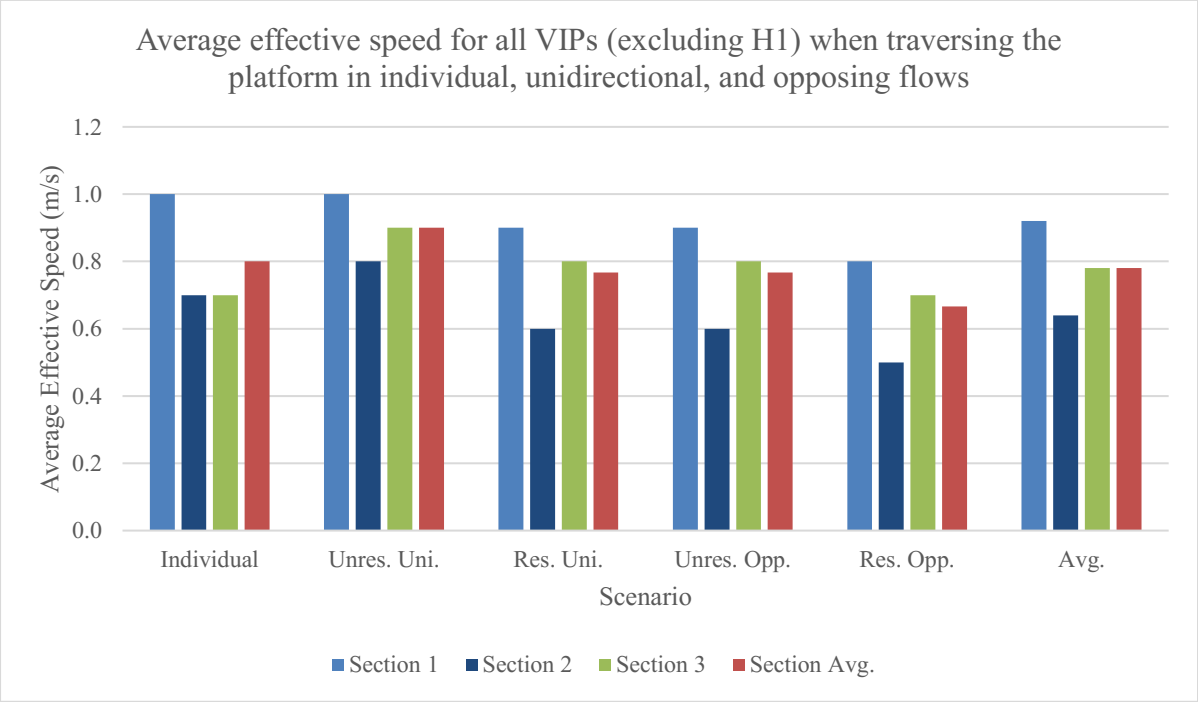


Figure 5.57: Average effective speed for all VIPs (excluding H1) when traversing the platform in individual, unidirectional, and opposing flows.

A fundamental conclusion is therefore that group conditions did not result in drastic differences on the overall effective performance of VIPs relative to their individual performance. Particularly, the unrestricted unidirectional flow introduced average performance improvements for the majority of VIPs. This is contrary to expectations according to the literature review. Moreover, section 1 consistently presented the best average effective

performance whilst, with exception to individual performance, section 2 presented the worst. This suggests that obstacles limited performance in all scenarios, and that larger obstacles (and the boundaries of environments) limited group performance to a larger extent than smaller ground level obstacles.

Table 5.11 lists the spread of results (SD and CV) for the average effective speed for all VIPs (excluding H1) when traversing the platform in individual, unidirectional, and opposing flows. The unrestricted unidirectional flow presented the smallest spread between sections, followed by the restricted unidirectional and unrestricted opposing flows, which were insignificantly different to individual performance in their spread of data. Finally, the restricted opposing flow provided the widest spread of data between sections, although this was also insignificantly different to individual performance. The unrestricted unidirectional flow therefore possessed the largest, but also most consistent, benefit to average effective performance relative to the other scenarios.

Metric	Individual	Unres. Uni.	Res. Uni.	Unres. Opp.	Res. Opp.
Avg. (m/s)	0.8	0.9	0.8	0.8	0.7
SD (m/s)	0.2	0.1	0.2	0.2	0.2
CV (%)	21.7	11.1	19.9	19.9	22.9

Table 5.11: Spread of average effective speed for all VIPs (excluding H1) when traversing the platform in individual, unidirectional, and opposing flows.

5.8.2. Summary Across VIPs

Figure 5.58 presents the average effective speed across sections for each VIP in each scenario ordered by increasing visual function. The VIPs were primarily arranged according to their group, then arranged according to their self-reported score of visual function within their group. VIPs with identical scores were arranged alphabetically within their group. Visually, it appears that there is a general positive trend to increasing visual function and effective walking speed. However, this relationship cannot be quantified given that VIPs' visual function was discretely categorised into four unevenly sized groups rather than clinically measured. Moreover, the exclusion of H1's opposing flow data within their average, on this occasion, further limits the data points available to define this relationship.

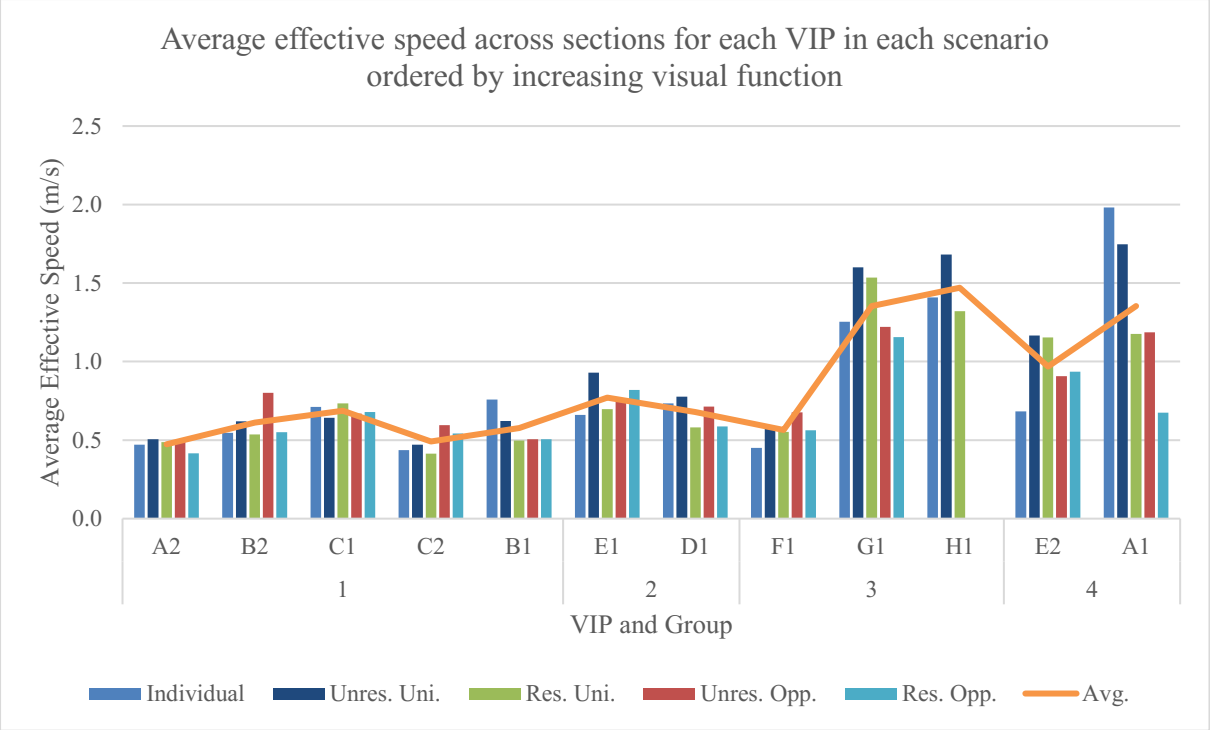


Figure 5.58: Average effective speed across sections for each VIP in each scenario ordered by increasing visual function.

Further analysis of each group's overall average supports this positive trend: across all sections and scenarios, group 1 yielded the lowest average effective speed of 0.6 m/s (SD = 0.1 m/s, CV = 16.7%), followed by group 2 at 0.7 m/s (SD = 0.1 m/s, CV = 14.3%), group 3 (excluding H1) at 0.9 m/s (SD = 0.4 m/s, CV = 44.4%), and group 4 with the highest value at 1.2 m/s (SD = 0.3 m/s, CV = 25.0%). There does not appear to be significance between the spread of the data and increasing visual function, likely a result of the small sample size within each group.

5.8.3. Hypothesis Testing

Fruin (1971) suggests that the walking speeds of pedestrians follow a normal distribution, and this was validated through empirical studies and applications in evacuation simulation models (Kinsey, 2015). To demonstrate this theory's applicability to this experiment, the times for VIPs to individually traverse section 1 of the platform have been plotted and shown to fit a normal distribution in Figure 5.59. Indeed, this is similarly observed in all other scenarios within the experiment where, when considering a sample of VIPs, a broad spread of data is presented with fewer outliers as effective performance deviates beyond the sample's mean effective performance.

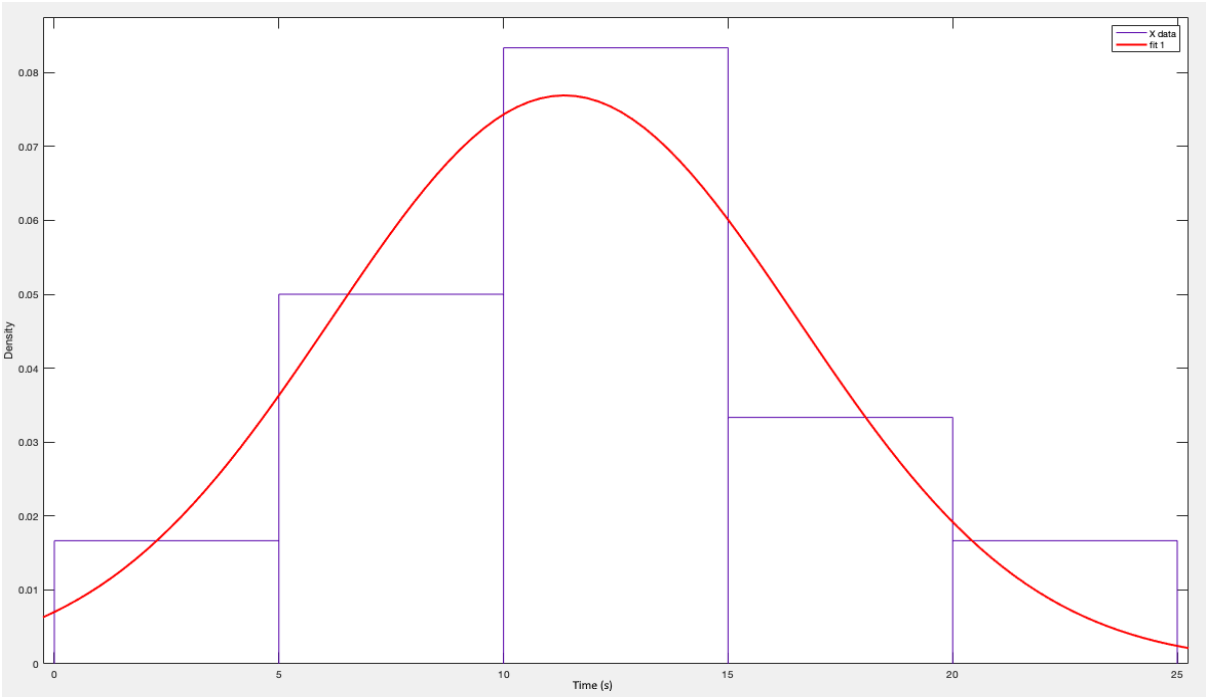


Figure 5.59: Normal distribution fitting the times for VIPs to individually traverse section 1.

Contrarily to the varying performance of each VIP, the literature review identified that disability continues to be modelled as a static performance-inhibiting constant attached to the agent's walking speed. To determine the validity of this approach, hypothesis testing is conducted, the full method for which is detailed in Appendix M. A significance level of 0.05 is employed, and the hypotheses observed are:

H_0: $\mu_A = \mu_B$

H_1: $\mu_A \neq \mu_B$

Where μ_A is the population mean of sample A and μ_B is the population mean of sample B.

Table 5.12 summarises the findings when comparing VIPs' effective performance in individual and unidirectional flows. Every pass is shown to be statistically different across each section of each scenario for VIPs, and the null hypothesis can therefore be rejected with 95% confidence. The modelling of VIP behaviour should therefore assign several velocities to different VIPs when considering their performance in individual and unidirectional group flows.

Section	Sample A	Sample B	p-value
Section 1	Individual	Unres. Uni.	0.68
	Unres. Uni.	Res. Uni.	0.41
	Individual	Res. Uni.	0.69
Section 2	Individual	Unres. Uni.	0.64
	Unres. Uni.	Res. Uni.	0.57
	Individual	Res. Uni.	0.95
Section 3	Individual	Unres. Uni.	0.06
	Unres. Uni.	Res. Uni.	0.40
	Individual	Res. Uni.	0.43

Table 5.12: Comparison of population means for VIPs' times to traverse each section in individual and unidirectional flows.

Table 5.13 summarises the findings when comparing VIPs' effective performance in individual and opposing flows. With the exception of individual versus unrestricted opposing flows, every pass is shown to be statistically different across each section of each scenario for VIPs. The null hypothesis can therefore be rejected with 95% confidence. The modelling of VIP behaviour should therefore assign several velocities to different VIPs when considering their performance in individual and opposing group flows.

Section	Sample A	Sample B	p-value
Section 1	Individual	Unres. Opp.	0.97
	Unres. Opp.	Res. Opp.	0.23
	Individual	Res. Opp.	0.33
Section 2	Individual	Unres. Opp.	0.49
	Unres. Opp.	Res. Opp.	0.52
	Individual	Res. Opp.	0.84
Section 3	Individual	Unres. Opp.	0.03
	Unres. Opp.	Res. Opp.	0.25
	Individual	Res. Opp.	0.39

Table 5.13: Comparison of population means for VIPs' times to traverse each section in individual and opposing flows.

Table 5.14 summarises the findings when comparing VIPs' effective performance in unidirectional and opposing flows. Every pass is shown to be significantly statistically different across each section of each scenario for VIPs, and the null hypothesis can therefore be rejected with 95% confidence. These three comparisons confirm that VIPs present very different performances across each scenario, particularly when observing unidirectional versus opposing performance. The current modelling of visually impaired behaviour should therefore incorporate variable walking speeds, rather than a constant.

Section	Sample A	Sample B	p-value
Section 1	Unres. Uni.	Unres. Opp.	0.38
	Res. Uni.	Res. Opp.	0.45
Section 2	Unres. Uni.	Unres. Opp.	0.83
	Res. Uni.	Res. Opp.	0.90
Section 3	Unres. Uni.	Unres. Opp.	0.82
	Res. Uni.	Res. Opp.	0.77

Table 5.14: Comparison of population means for VIPs' times to traverse each section in unidirectional and opposing flows.

5.8.4. Summary of Questionnaire Results

VIPs were asked whether or not the presence of other NSPs affected their behaviour during group scenarios. Here, 9 of 12 VIPs explained that NSPs did affect their behaviour, and the majority of responses (7 of 9) confirmed that this was to the benefit of the VIP's performance. Particularly, B1, C1, C2, D1, E1, E2, and H1 all referenced NSPs as either providing a sense of protection, or that the NSP was used as a guide. For instance, D1 explained that they kept to the NSPs' speeds, while E2 found NSPs particularly useful when navigating section 2 and section 3.

C1 and H1 explained that NSPs guided them beyond visual coupling, with C1 stating that NSPs acted as a guide 'even when they were not there'. H1 used auditory feedback to determine the

position of NSPs, stating that this would be more problematic had an alarm been on. Indeed, this is in keeping with the conclusions that group flows do not necessitate a reduction of performance for VIPs; rather, VIPs are likely to experience improved performance as a result of their interactions with NSPs.

The presence of multiple VIPs on the platform in opposing flows did result in unique interactions, particularly poor decision making and collisions. This was thought to have an effect on each VIP's actions. Indeed, according to the questionnaire, 6 of 8 VIPs that interacted with another VIP on the platform expressed sentiment on being aware of the VIP, taking more care, or being apprehensive to avoid a collision. For instance, E2 expressed that they 'could hear [the other VIP's] cane', while C2 explained that it 'made me much more aware, especially if they were going to collide'.

Interestingly, B2 stated 'I had to be comfortable with my speed to make sure I was safe'. This suggests that effective performance within the opposing flows was not exclusively dependent on the immediate interaction of the opposing groups (and VIPs). Rather, each VIP may have regulated their walking speed from the beginning of the opposing pass. A limitation of this experiment is therefore that the presence of another VIP was not controlled within every session given limitations in participant recruitment. Future work should investigate opposing flows with a controlled number of VIPs. This is relevant for group dynamics studies in hospitals, care homes, or other spaces with a higher prevalence of visually impaired occupants.

NSPs were asked to discuss whether or not the presence of VIPs on the platform affected their actions. Of 44 responses, 38 stated that the VIP did impact their actions. 26 of these responses expressed sentiment on being aware of the VIP, including hesitance or slowing down as a result. 19 responses referenced avoidance of collisions or bumping into the VIP or their cane. Notably, of the 11 NSPs that specifically mentioned the VIP's cane in this context, 2 described that the cane's sweep created a wider area that had to be avoided. To similar effect, responses indicating additional awareness of the VIP were likely to also reference the VIP's dominance of the flow, acting as 'slow-moving' or 'non-uniform' obstacles to NSPs and preventing overtaking manoeuvres. EN1 described this as being 'trapped behind' the VIP.

Behaviours observed within the video footage are confirmed within specific NSP responses. For instance, AN2 explained that the restricted scenarios were slower than their unrestricted counterparts, while the opposing flows had the higher chances of collisions. GN2 referenced turning back to check on the VIP, as did HN7 in stating that they had to look around more often. Moreover, EN8, HN2, and HN3 confirmed that NSPs were responsible for unilateral decision-making given the VIPs' reduced visual function. This resulted in the NSP increasing their speed when given the chance to do so to avoid contact, such as HN1 and HN4 when positioned ahead of a VIP using a cane. Contrastingly, this behaviour could aid the VIP in orientation, as it did for H1. It is concluded that VIPs are significantly more likely to benefit in group versus individual performance relative to NSPs, where the opposite is true.

5.9. Variations and Additions to the Experimentation

5.9.1. Varying the VIP's Position within the Group

Throughout sessions A-G, the VIP was positioned at the front of their group to allow them the best chance of remaining in (and interacting with) their group, rather than being left behind.

Consequently, in all group scenarios (particularly in restricted passes), the VIP was found to dominate the flow. Group members behind them had a lower likelihood of overtaking, a result of physical and psychological constraints. NSPs felt uncomfortable in encroaching on the VIP's space or were unable to complete a manoeuvre given the VIP's space requirements, especially with cane usage.

To evaluate the impact of the VIP-NSP positioning on performance, VIP H1 was positioned in several positions within their group in a unidirectional and opposing flow. The unidirectional flow is explored first; here, H1 was positioned at the front of the group and restricted and unrestricted passes for each section were conducted. H1 was then positioned at the rear of the group and the experiment was repeated. H1 was intentionally used for this demonstration given that they were a fast-moving cane user, and were likely to not get left behind if positioned at the rear of the group. The time for H1 to traverse the platform in these different configurations is presented by Figure 5.60.

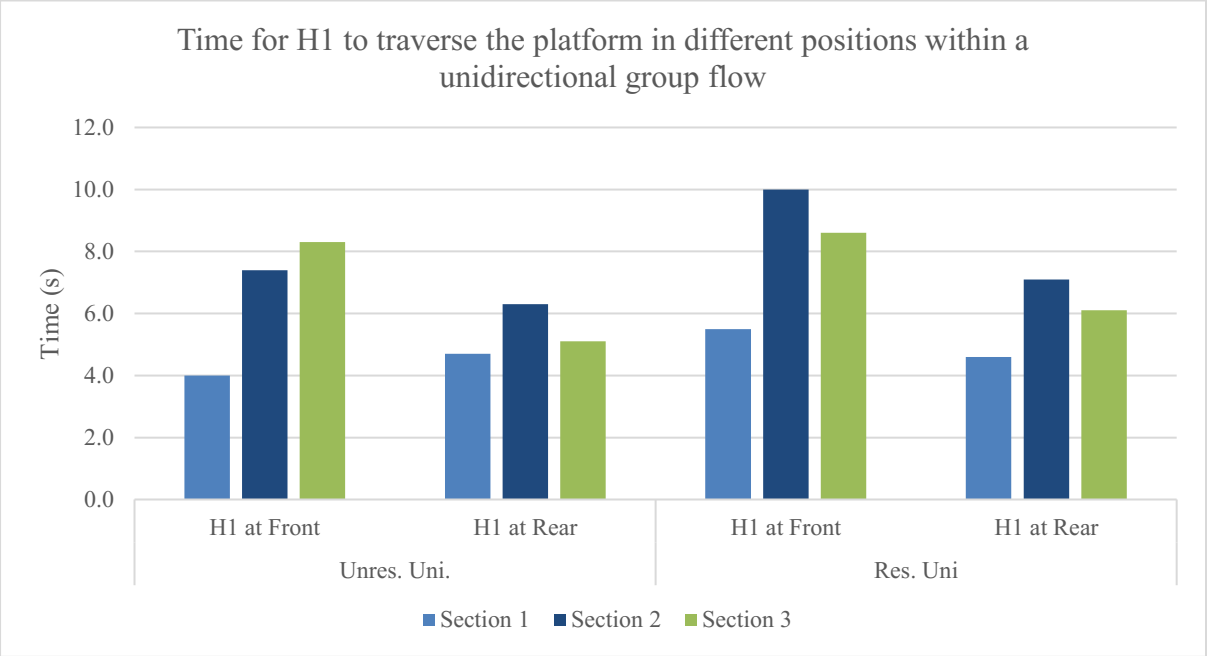


Figure 5.60: Time for H1 to traverse the platform in different positions within a unidirectional group flow.

Considering the unrestricted unidirectional flow, H1 yielded a mean time to traverse the platform of 6.6 s (SD = 2.3 s, CV = 34.5%), and 5.4 s (SD = 0.8 s, CV = 15.5%) when at the rear. This represents a mean percentage change from individual performance of -11.9% and -18.1%, respectively. Therefore, H1 presented a better, and more consistent, effective performance when at the rear of the group in this scenario.

Similarly, in the restricted condition, H1 yielded a mean time to traverse the platform of 8.0 s (SD = 2.3 s, CV = 28.7%), and 5.9 s (SD = 1.3 s, CV = 21.2%) when at the rear. This represents a mean percentage change from individual performance of 9.2% and -18.7%, respectively. The restricted condition, as expected, yielded a slower pass than the unrestricted condition when the experiment was conducted with the VIP at the front. However, positioning H1 at the rear of the restricted flow had a significant improvement on their performance, exceeding that from the unrestricted pass with H1 at the front.

When surveyed, H1 expressed a strong coupling with NSPs around them when moving, including tactile identification through using their cane or brushing against people's shoulders to orientation. This was observed throughout these passes, as demonstrated by Figure 5.61. Here, H1 is shown at the front and rear of an unrestricted unidirectional flow. As H1 was fast moving, they were still able to maintain their position leading the group, although this reduced their ability to couple with a leading NSP. Contrastingly, when at the rear, H1 coupled with the NSP ahead of them, tapping the NSP with their cane and pressuring faster forward motion while overtaking another NSP.

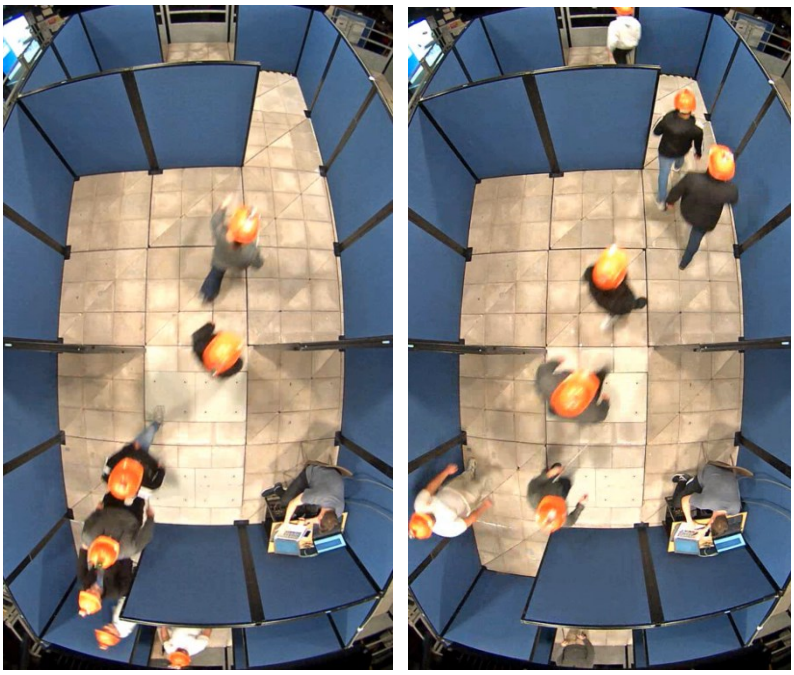


Figure 5.61: VIP in an unrestricted unidirectional flow when positioned at the front (left) and rear (right) of the group.

Two configurations were observed for both unrestricted and restricted opposing flows. One is where the VIP is in a group of NSPs going against a single NSP, and the other is where a group of NSPs is going against a single VIP. Figure 5.62 presents the results from both configurations in an unrestricted opposing flow. When in group, H1 yielded a mean time to traverse each section of 6.3 s (SD = 1.4 s, CV = 22.5%), and, when alone, this decreased to 5.9 s (SD = 0.7 s, CV = 11.3%). Comparatively, HN2 presented a mean time of 7.4 s (SD = 1.5 s, CV = 19.6%) when in group, and 6.6 s (SD = 0.9 s, CV = 13.0%) when alone.

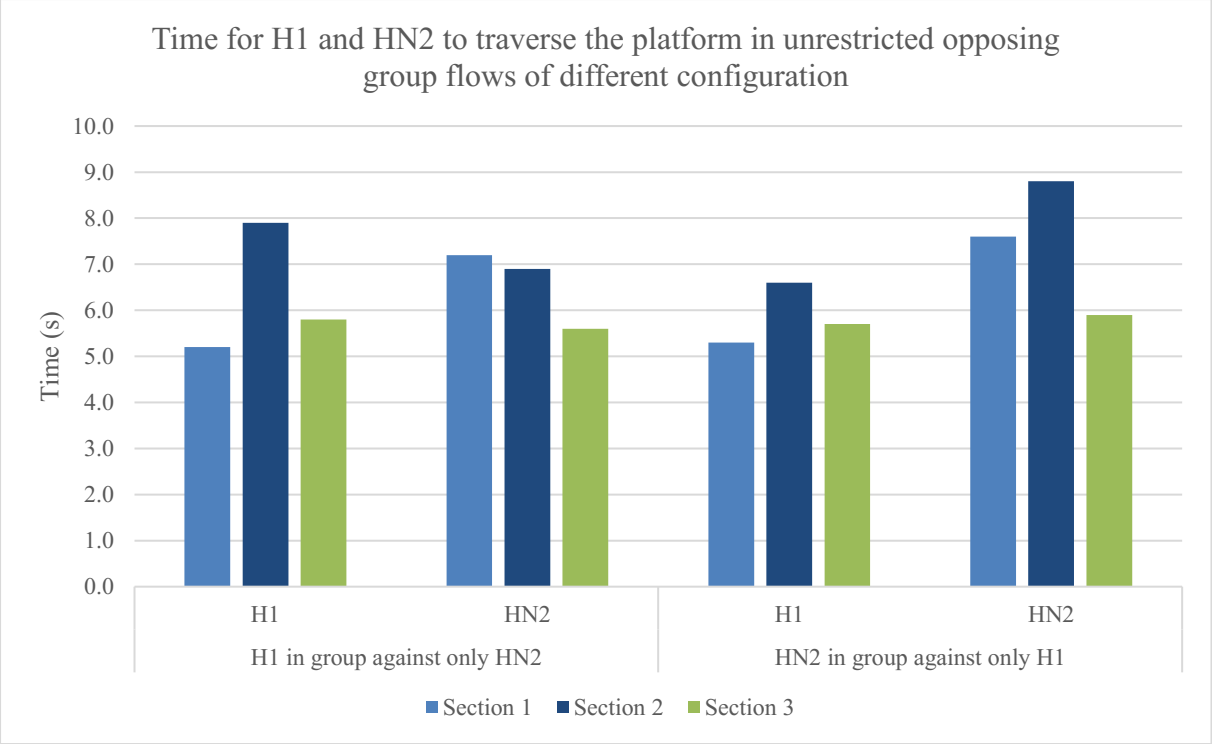


Figure 5.62: Time for H1 and HN2 to traverse the platform in unrestricted opposing group flows of different configuration.

Indeed, H1 is a fast-moving VIP and presented a mean effective performance that was better than that of the NSP in both positions. As is typical for VIP-NSP performance changes in group, the VIP experienced an average increase in performance from baseline (-13.0% and -18.7% in each configuration) while the contrary was true for the NSP (29.6% and 14.3% in each configuration). Interestingly, both the VIP and NSP demonstrated improved performance when opposing a group on their own. This was unexpected for the VIP as they had a better performance when interacting within a group (as shown in the unidirectional flow when positioned at the rear of the group). Figure 5.63 displays the results of these configurations when repeated in a restricted opposing flow.

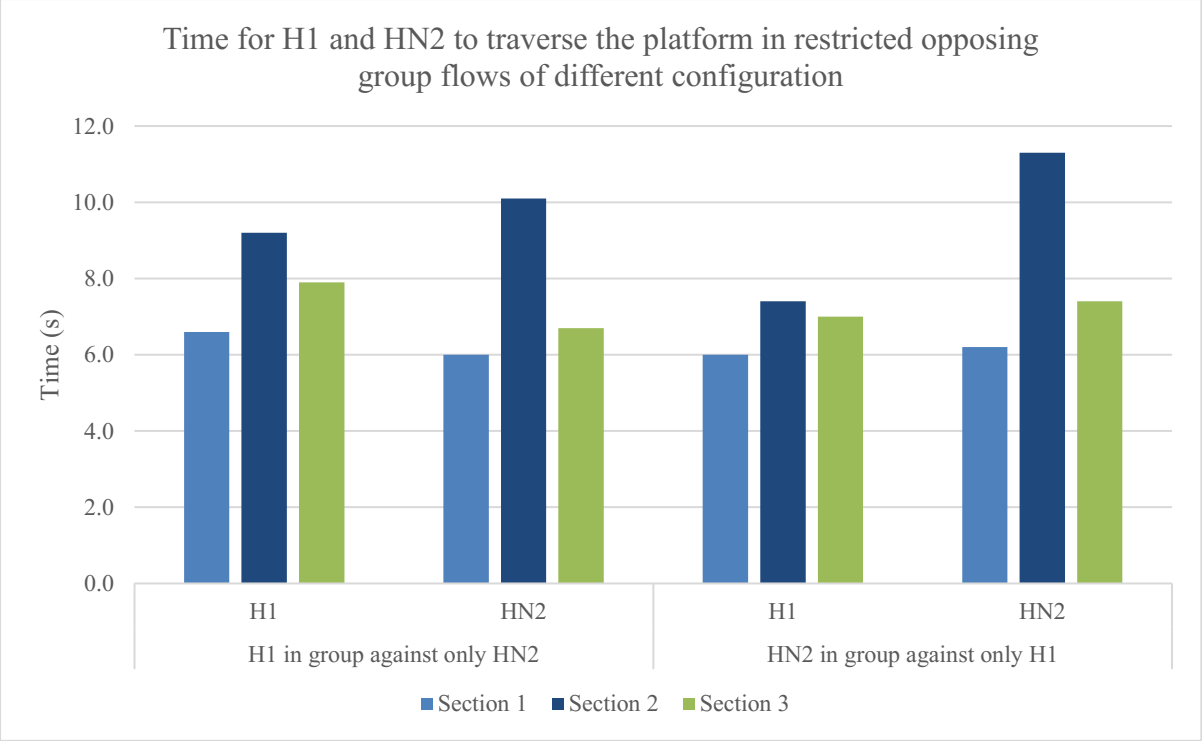


Figure 5.63: Time for H1 and HN2 to traverse the platform in restricted opposing group flows of different configuration.

When in group, H1 yielded a mean time to traverse each section of 7.9 s (SD = 1.3 s, CV = 16.5%), and, when alone, this decreased to 6.8 s (SD = 0.7 s, CV = 10.6%). Comparatively, HN2 presented a mean time of 8.3 s (SD = 2.7 s, CV = 32.1%) when in group, and 7.6 s (SD = 2.2 s, CV = 28.9%) when alone. All observations from the unrestricted opposing flow therefore prevailed under the restricted condition.

Furthermore, in keeping with observations from all other sessions, the restricted condition led to a slower pass for all members than its unrestricted counterpart. With respect to effective performance from baseline, H1 experienced an average decrease of 8.8% in group, and an average increase of 6.1% when operating alone. HN2 experienced average performance decreases of 32.5% and 44.6% when in group and alone, respectively. In group, the VIP continued to use their cane to orientate and keep up with the preceding NSP, as illustrated by Figure 5.64 and also found in the unidirectional scenarios.



Figure 5.64: VIP keeping up with an NSP by tapping their cane against them.

In conclusion, the position of the VIP within a group can impact both the group and the VIP's performance. H1 was a fast-moving VIP, and uncertainty remains as to how a slower-moving VIP may be affected, especially if left behind by the group. This example serves to highlight the relevance of the VIP's position within the group to effective performance, a characteristic that was not identified within the existing literature review.

5.9.2. Unidirectional and Opposing Flows without VIPs

The behaviours displayed by NSPs throughout the experiment were unexpected in instances. This is exemplified by the unilateral decision making in opposing flows where decisions made by NSPs impeded on the VIP and the remainder of the group. As such, further experimentation of the behaviours of NSPs without VIPs' influence was proposed and conducted across three sessions. Session 1 involved a smaller group of 8 NSPs, while session J was conducted with a larger group of 14 participants. The sessions only contained opposing flows, and both unrestricted and restricted conditions were implemented.

Session I was intended as exploratory, assessing whether NSPs did indeed significantly contribute to the safety and success of a pass. Two configurations were tested; one where IN1 was in a group that went against only IN2, and another where IN1 and IN2 were in opposing groups of equal size. Figure 5.65 summarises the results from both configurations in an unrestricted and restricted opposing flow.

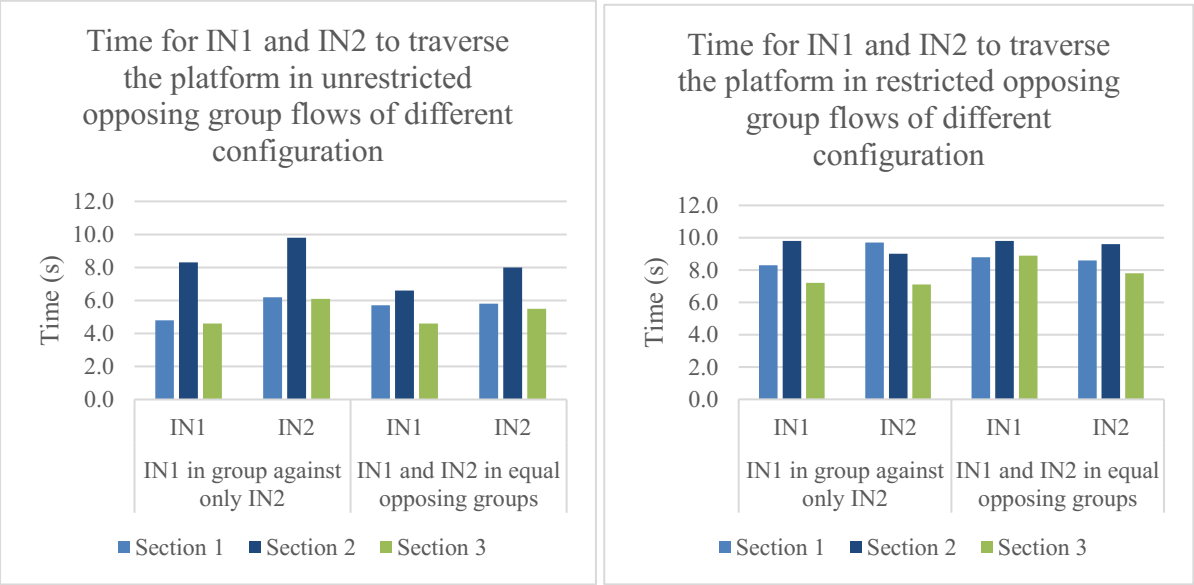


Figure 5.65: Time for IN1 and IN2 to traverse the platform in unrestricted and restricted opposing flows of different configurations.

The restricted flow led to reductions in effective performance across all sections relative to the unrestricted flow. In the unrestricted flow, positioning in equal groups was more effective for both NSPs than when only one NSP was going against the group: the mean time for IN1 and IN2 to traverse all sections decreased from 5.9 s to 5.6 s, and 7.4 s to 6.4 s, respectively. Consistency across sections also improved, where the CV for IN1 and IN2's results decreased from 35.3% to 17.8%, and 28.6% to 21.2%, respectively. These represented an average change of -23.3% and -25.9%, and -8.6% and -19.7% from the times for IN1 and IN2 to traverse the platform individually.

Interestingly, group formation did not have such an effect on the restricted condition. Here, the mean time for IN1 and IN2 to traverse all sections increased from 8.4 s to 9.2 s, and 8.6 s to 8.7 s, respectively. Consistency across sections continued to improve, however, and the CV for IN1 and IN2's results decreased from 15.5% to 6.0%, and 15.6% to 10.4%, respectively. These represented an average change of 11.2% and 22.0%, and 9.3% and 9.2% from the times for IN1 and IN2 to traverse the platform individually.

Displayed in Figure 5.66, the two-wide formation maintained by the opposing group in the restricted flow inhibited the motion of NS2. Contrastingly, the group was moving sufficiently quickly in the unrestricted flow to form a lane as members followed one another while trying to keep up. This behaviour remains surprising, more so in the restricted condition where decision making should have been bilateral. It was expected that each NSP would visually identify an optimal route and move to avoid collision. Instead, a three-wide formation was created as IN2 centrally bifurcated the opposing lanes.



Figure 5.66: Single NSP interacting with an unrestricted (left) and restricted (right) opposing flow of other NSPs.

A similar finding occurred when observing the equal restricted opposing group formations. Once again, the groups maintained a two-wide formation and collided, even when no VIP was present to dominate the flow or hinder bilateral decision making. However, arrangements into lanes did appear to be faster in all instances upon correction. Figure 5.67 illustrates such an occurrence. This may explain why better performance was observed when this formation was employed instead of one with a larger group and single NSP. As a result of these unexpected findings, session J was planned and executed with a larger group of NSPs to better understand these behaviours.



Figure 5.67: Small equal opposing groups of NSPs colliding in a restricted opposing flow.

Session J involved the same group of 14 NSPs split equally into two opposing groups. Two passes of each an unrestricted and restricted opposing flow for every section of the platform were conducted. JN1 and JN2 were NSPs in opposing groups that were randomly selected and fixed throughout the experiment for closer observation. Their times to complete each pass is presented in Appendix H. Figure 5.68 presents the time for each NSP to traverse the platform for each section of each pass.

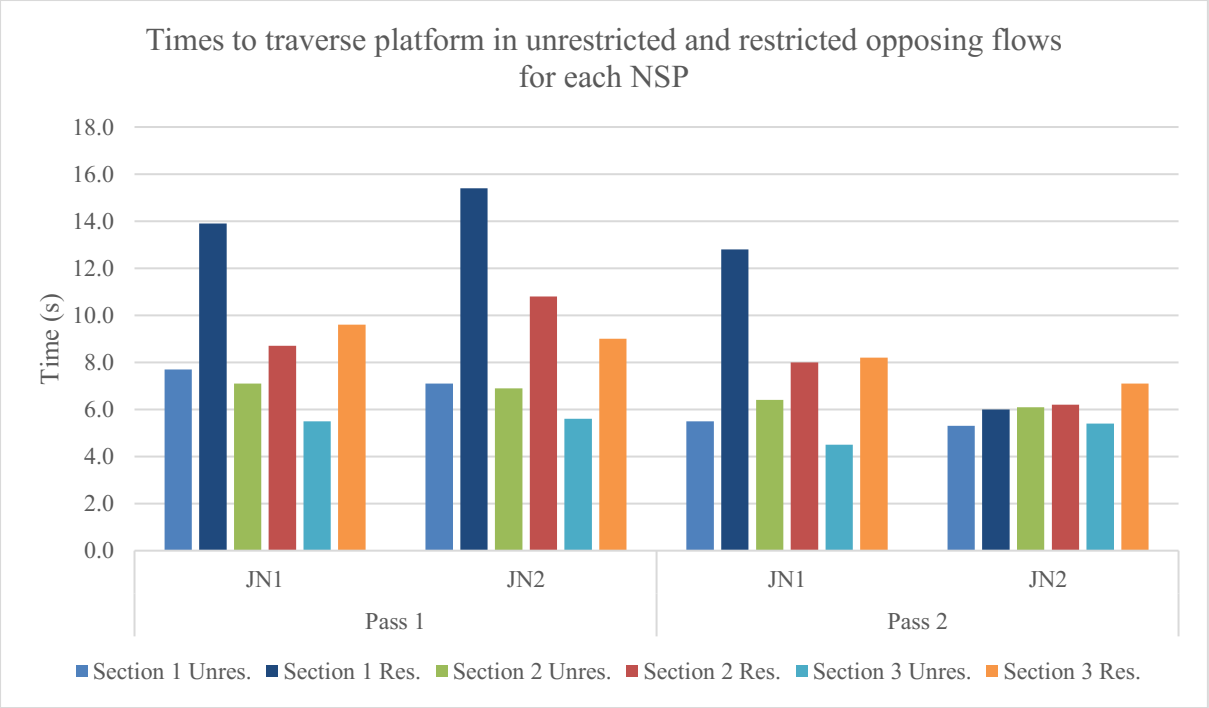


Figure 5.68: Times to traverse platform in unrestricted and restricted opposing flows for each NSP.

As in the case of VIPs, NSPs experienced better effective performance in the unrestricted passes relative to the restrictive passes. This prevailed in this instance even with increased group densities. In moving from an unrestricted to restricted flow, the mean time to traverse each section (including both passes and NSPs) rose from 6.4 s to 12.0 s for section 1, 6.6 s to 8.4 s for section 2, and 5.3 s to 8.5 s in section 3. Notably, sections 2 and 3 presented the best overall average performances, especially in section 3's unrestricted opposing flows. This is contrary to VIP performance where section 1 prevailed as the best performing section. Indeed, section 3's increased width likely prevailed over its inclusion of obstacles for NSPs. Figure 5.69 displays the effective speed of each NSP traversing the platform under these scenarios.

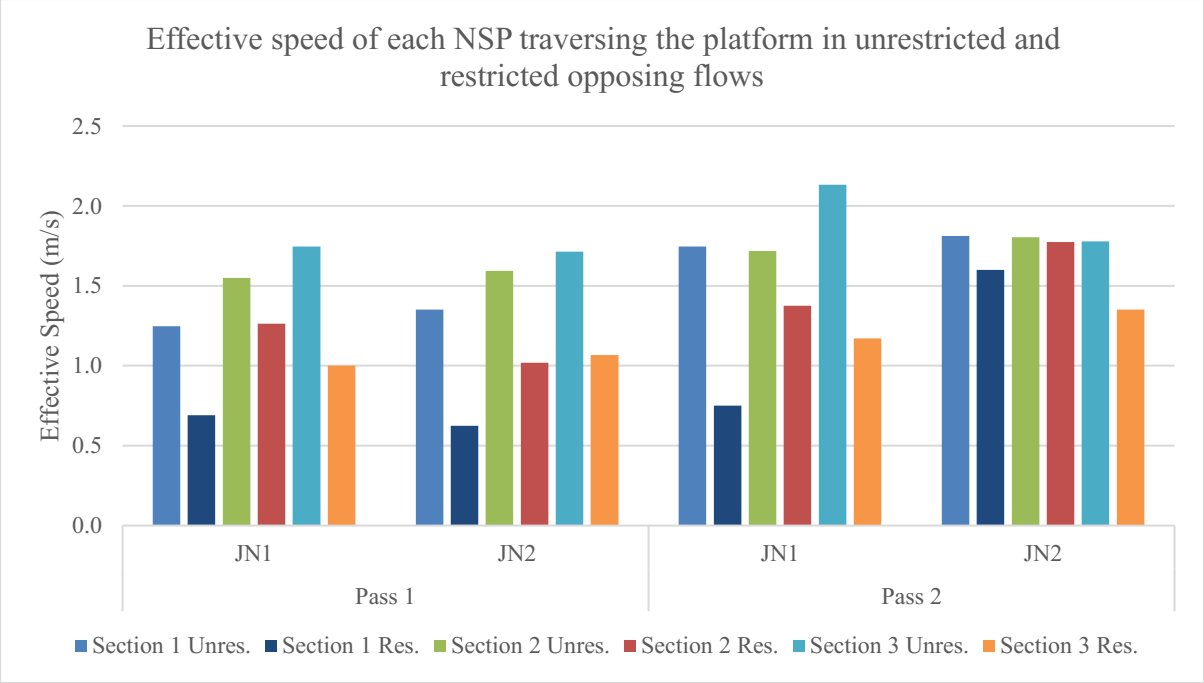


Figure 5.69: Effective speed of each NSP traversing the platform in unrestricted and restricted opposing flows.

In moving from an unrestricted to restricted flow, effective speed fell from 1.5 m/s to 0.9 m/s in section 1, 1.7 m/s to 1.4 m/s in section 2, and 1.8 m/s to 1.1 m/s in section 3. It is noted that these effective speeds all lie above the average performance of the VIP sample in every scenario. This further confirms the NSPs' performance advantage when VIPs do not dominate the flow. Interestingly, the spread of results was significantly dependant on flow restriction. In comparing the unrestricted and restricted condition, CV increased from 18.3% to 50.1% in section 1, 7.0% to 23.2% in section 2, and 10.6% to 13.4% in section 3. Excluding section 1's restricted opposing flow, the NSPs' effective performance within sections was therefore significantly more similar than that of the VIPs.

Section 3 presented the lowest variation in data spread than the other sections, while section 1 presented the highest. Once again, this is likely given section 3's wider width, and the lesser resulting impact of flow type on the ability of participants to manoeuvre around each other. From pass 1 to pass 2, JN1's average effective speed across all sections and scenarios increased from 1.2 m/s to 1.5 m/s, while JN2's increased from 1.2 m/s to 1.7 m/s. A larger sample size is needed to determine if NSPs improve performance in repeated crowd scenarios with statistical significance. A conclusion that arises is that these NSPs presented a better effective performance than all VIPs in all scenarios, even given the poorer performing restricted opposing flow. Figure 5.70 displays the percentage change between times to traverse the platform in the unrestricted versus restricted condition of the opposing flow.

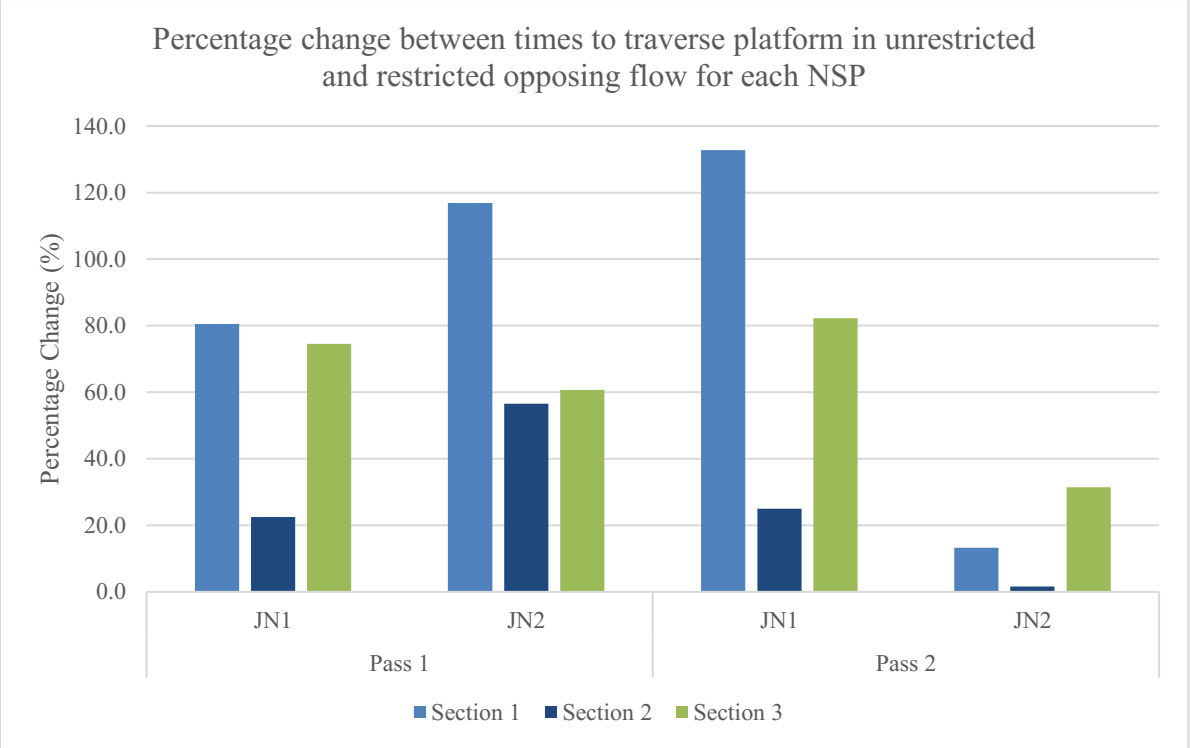


Figure 5.70: Percentage change between times to traverse platform in unrestricted and restricted opposing flow for each NSP.

The significance of the change in performance between these two conditions was dependant on both the section and NSP. For instance, the average percentage changes for sections 1, 2, and 3 were 85.8%, 26.4%, and 62.2% respectively, whereas, when comparing across NSPs, JN1 and JN2 experienced respective average percentage changes of 59.2% and 78.0% across all sections in pass 1, and 80.0% and 15.4% across all sections in pass 2. The NSPs in this scenario presented better effective performance than those in groups with VIPs.

The consistently negative impact on performance on introducing a restricted condition is further explored. Video footage from a restricted pass in section 1 demonstrates the compact shoulder-to-shoulder formations adopted by NSPs in a restricted opposing flow. Figure 5.71 displays how NSPs walk in pairs, presenting a 'lock-step' characteristic as described in Seyfried et al. (2005). This behaviour was not found in passes with VIPs and was likely a consequence of the non-uniform walking patterns of VIPs. NSPs' questionnaire responses support this finding. Behaviours from Seyfried et al. (2009) are demonstrated as NSPs provisioned more space for VIPs to manoeuvre, but did not do so when the VIP was removed in this scenario.



Figure 5.71: NSPs walking in a compact formation in a restricted opposing flow without VIPs.

As a result, the insistence of NSPs to remain in this formation as they traversed the section resulted in slower walking speeds and increased collisions. Lanes did not form until NSPs collided, in a similar fashion to when VIPs where included. However, increased performance was still obtained relative to restricted opposing flows with VIPs as the NSPs were able to correct their path to overcome the opposing group following collision. Figure 5.72 demonstrates such an incident.



Figure 5.72: NSPs colliding in a restricted opposing flow resulting from delayed lane formation.

Figure 5.72 further highlights the high densities thar occurred within these opposing flows, particularly in section 1 where 5.21 persons/m^2 was observed in this instance. Such is the reasoning for section 1's poorer relative performance to the other sections, exemplifying the inverse relationship between speed and density (Weidmann, 1992). Contrastingly, section 1 prevailed as the best performing section, on average, for VIPs in all scenarios. This suggests that density was not the limiting factor for VIP performance. Figure 5.73 plots the walking path and speed of an NSP traversing in the restricted opposing flow in section 1. The walking path moves from right to left, and a clear dip in walking speed can be observed between 8 and 12 s into the pass where the opposing group is encountered at high density.

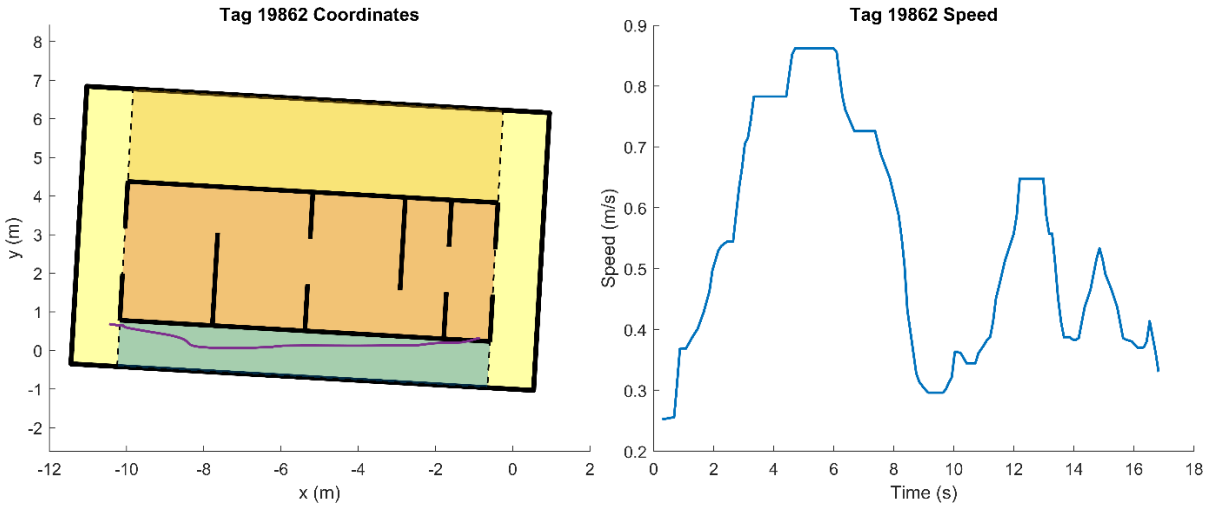


Figure 5.73: Coordinate and speed plot of an NSP encountering a high-density restricted opposing flow in section 1.

Of particular note is the inefficient path taken by the NSP. Having started closer to the wall in a two-wide formation, this NSP had to merge into a single lane to avoid collision with the opposing group, suddenly moving back to their original path between x = -8 m and x = -10 m on emerging from the area of high density. In conclusion, this demonstrates that, in a restricted opposing flow, the removal of the VIP did not necessitate better decision-making by NSPs. Instead, greater freedom for NSPs led to increased maintenance of group formations, lockstep,

and higher densities. These resulted in performance reductions for different reasons than those arising from the presence of VIPs.

In contrast to the restricted condition, the unrestricted opposing flows generated aggressive NSP behaviours, including high speed overtaking and collisions. Indeed, the largest percentage difference between the time for a VIP and NSP to traverse the platform in an unrestricted opposing flow was found to be 200.8% in section 2. Figure 5.74 displays one such example where, even though lanes had formed, the highlighted NSPs proceeded to collide at a high speed given insufficient time to react and manoeuvre. Interestingly, six high speed collisions between NSPs were recorded in session J in unrestricted opposing flows, whereas none were noted throughout unrestricted opposing flows containing VIPs.

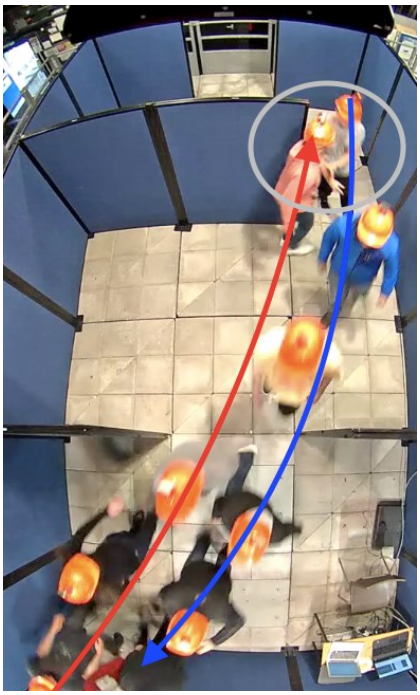


Figure 5.74: NSPs colliding in an unrestricted opposing flow of high speed.

Figure 5.75 produces the coordinate and speed plots of the NSP involved in this incident. The direction of motion is from left to right. It can be seen that the NSP accelerates to 1.4 m/s, a speed seldom reached by NSPs and VIPs in prior speed plots. A sudden deacceleration follows to maintain a speed of approximately 0.5 m/s upon encountering the opposing flow at the section midpoint. This is shown to affect the NSP's path at x = -6 m as a sharp turn and correction.

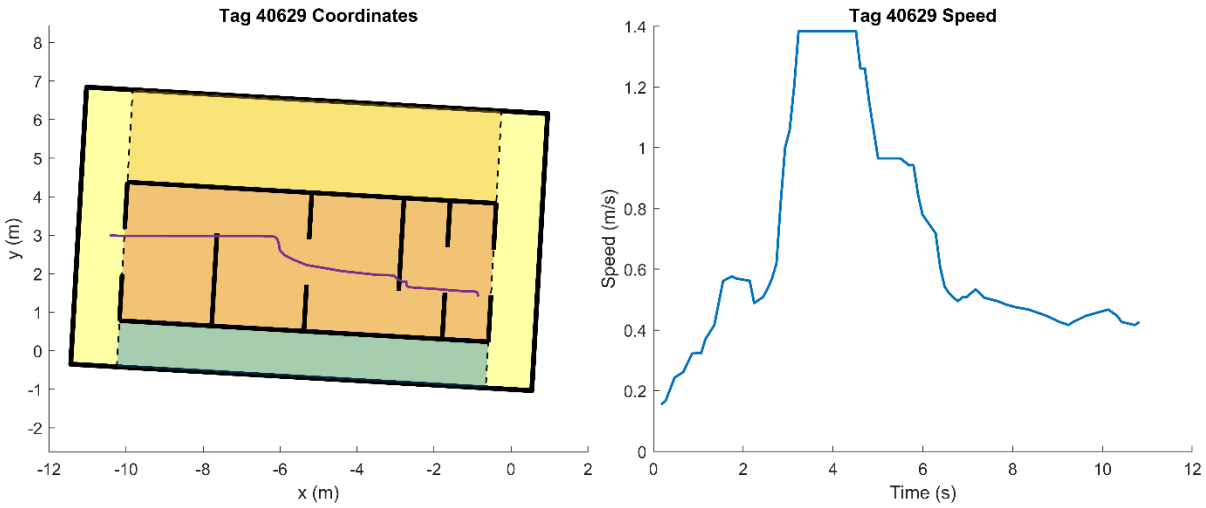


Figure 5.75: Coordinate and speed plot of an NSP colliding and slowing down in an unrestricted opposing flow.

Therefore, while the unrestricted opposing flows were much faster with only NSPs, safety was compromised. In dominating the flow (and even colliding with opposing group members), the VIP reduced NSPs' freedom of movement and pressured the group to abstain from higher speed manoeuvres. This ultimately led to smoother and more controlled flows than those excluding the VIP.

These findings were confirmed through the questionnaire results. Here, out of a comfort score from 1 (least comfortable) to 5 (most comfortable), participants in session J scored an average of 2.8, 2.7, and 3.4 in sections 1, 2, and 3, respectively. Section 3's width benefit is therefore supported, even when given the ground-level obstacles present within it. Moreover, all but one participant preferred the restricted to the unrestricted opposing flow. Subsequently, the restricted opposing flow scored significantly higher, on average, than the unrestricted condition at 3.2 versus 1.9.

5.10. Conclusions from the Experiment

5.10.1. Conclusions on VIP Behaviour

From all scenarios involving VIPs acting in groups, it is evident that the VIP dominated the flow, both in its speed and safety. This could be to the benefit or detriment of group members; for instance, if the VIP walked uniformly (such as tracing a boundary), NSPs consistently provided them with sufficient space as to avoid collision. In opposing flows, this benefited lane formation through the natural organisation of NSPs behind the VIP as a result of their slower walking speed. Contrarily, if the VIP adopted a non-uniform walking behaviour (such as one with sudden changes in direction or excessive cane movement), turbulence and poor unilateral decision making from NSPs arose, particularly in opposing flows where the VIP obstructed the path of the oncoming group.

Sections 1 and 2 yielded the phenomenon of opposing groups coming to a temporary halt through a deadlock resulting from a VIP collision in a narrow walking path. Interestingly, the physical contact and manoeuvring of VIPs through group forces was necessary for lane formations to overcome this. Findings from Samoshin & Istratov (2014) are iterated in that

VIPs would touch objects to determine their presence, and form lanes only upon contact with other individuals.

The unrestricted and restricted condition within each group scenario generated differences in performance and walking behaviour that exceeded the initial hypotheses of this study. Firstly, considering the VIP sample's average effective performance, group scenarios predominantly matched or exceeded individual performance. The unrestricted unidirectional condition best demonstrates this where 75% of VIPs experienced an increase in effective performance from their individual passes of the platform. Contrarily, the restricted opposing flow yielded the worst average performance of all scenarios, and only 45% of VIPs experienced an increase of effective performance from their individual passes of the platform.

However, the unrestricted condition motivated undesirable behaviours within the group, including aggressive overtaking manoeuvres by NSPs, collisions, stop-start waves, turbulence, and the disorientation of VIPs. Contrastingly, the restricted condition enabled smoother flows, and VIPs were less likely to be left behind the group as NSPs maintained the group's formation. Such was reflected in VIPs' questionnaire responses where the scenarios were ranked from best to worst as follows: restricted unidirectional flow, unrestricted unidirectional flow, individual, restricted opposing flow, unrestricted opposing flow. In a realistic scenario, a restricted flow would therefore be preferable for VIPs as its enhanced safety and ease of lane formation outweighs the effective performance benefits of an unrestricted flow.

In all group scenarios, VIPs utilised the NSPs around them to orientate, be it through visual, auditory, or haptic coupling. Not only did this enable VIPs to match NSP performance under restricted conditions, but also enhanced VIPs' walking path efficiency and avoidance of obstacles. Unidirectional flows allowed for this behaviour throughout the entirety of the pass. Opposing flows, however, were not desirable as, regardless of flow restriction, collisions and deadlocking prevailed, particularly as NSPs conducted unilateral decision-making on encountering opposing VIPs.

Correspondingly, a positive correlation was found between walking speed and self-reported comfort when VIPs traversed the platform individually. This correlation was maintained in a unidirectional flow, but completely diminished in an opposing flow. It can therefore be concluded that, in undesirable group conditions, VIPs' control of their walking behaviour decouples from their own psychological state, and couples with the state of the crowd.

5.10.2. Conclusions on NSP Behaviour

NSPs emphasised contact avoidance with the VIP in their presence, often slowing down and maintaining formation behind the VIP. In turn, this enabled natural lane formations, especially in opposing conditions where, albeit inconsistent in outcome, NSPs anticipated and avoided the opposing VIP through unilateral decision making. In considering only effective performance, NSPs demonstrated significant and consistent reductions in their times to complete all sections of the platform when the VIP was removed from the group, although such did not necessitate improvements in flow safety.

NSPs presented reductions in effective performance in restricted versus unrestricted conditions. In restricted flows, NSPs maintained a line-abreast group formation that contrasted with the river-like movement in unrestricted flows, as defined in Moussaid et al. (2010). The

latter resulted from elevated, yet varied, walking speeds as NSPs followed behind one-another, keeping up where possible. Consequently, in opposing flows, the ineffective maintenance of group formations led to collisions in restricted passes, while these prevailed at higher speed in unrestricted passes. NSPs therefore preferred the restricted condition, as did VIPs.

In the presence of VIPs, the narrowest section (section 1) yielded the best VIP performance relative to other sections (and this extended to NSPs in restricted conditions as their performance would match that of the VIP). On removing the VIP, the widest section (section 3) yielded the best NSP performance relative to other sections. It can therefore be concluded that the VIP limited the flow in group scenarios, particularly in sections with obstacles (sections 2 and 3). Contrarily, density limited the performance of NSPs operating without a VIP. Therefore, the classical relationship of speed-density is applicable to NSPs operating without a VIP but is not applicable upon the introduction of the VIP.

5.10.3. Limitations and Recommendations

This experiment investigated the physiological and psychological performance of VIPs with varying visual impairments acting individually, and in unidirectional and opposing group flows. A controlled environment with and without obstacles was employed. This novel combination of factors has not been explored in prior studies; for instance, Sharifi et al. (2016) included VIPs in their study of a large crowd egress, although crowd formation (such as unidirectional and opposing flows) were not controlled. No further investigation into the individual ability of the visually impaired participants was conducted. The experimentation conducted within this thesis improves upon this by deeply observing the changes in behaviour and performance across individual VIPs when operating alone and in controlled group settings.

To similar effect, Lam et al. (2003) observed variations in walking speed across opposing group flows. However, this did not include VIPs, and only NSPs formed the participant sample. The significant impact on the group induced by the VIP, as proven within this thesis, was therefore not found. Moreover, this thesis is novel in that it correlated the self-reported psychological performance of VIPs and NSPs as group conditions varied, providing microscopic insight into each agent's actions while also monitoring the resulting macroscopic effects on the crowd.

This is a profound contribution from this study, particularly in that existing models insufficiently associate a static reduction in walking speed to simulate VIP behaviour relative to NSPs. For example, in their extended BUMMPEE model, Koo et al. (2013) represented a VIP as possessing a horizontal walking speed of 0.86 m/s, without considering variations on encountering obstacles or the group scenarios established within this thesis. This is simplistic, and contrary to the analysis conducted within this thesis to prove the wide-ranging VIP performance in different group scenarios. Furthermore, this study established that individual, unidirectional, and opposing flows (including restricted and unrestricted conditions) should each be considered in models given the significant variations in group behaviour between them.

In yielding novel findings, this experimentation also reaffirmed conclusions from existing literature. Particularly, lane formations, bottlenecks, deadlocking, and interactions at intersections, as first studied by Helbing et al. (2002), were observed. As was the emergence of self-organised formations in Moussaid et al. (2016), conducted by NSPs throughout all group scenarios. Moreover, the classical inverse relationship between speed and density was

preserved in NSP-only group conditions (Weidmann, 1992). Therefore, while novel VIP behaviours have been described, the realistic performance of NSPs, as simulated in various prior studies, strengthens the validity of this experiment.

This experimentation is not without limitations and, while it has extracted novel VIP-NSP group behaviours, it has not exhaustively done so. This is given the multitude of visual impairments and operational scenarios that exist but could not be represented in this study. The logistical limitations of participant recruitment and clinical visual function testing also hindered the depth in which speed, density, and visual function could be correlated. However, the breadth of participants' visual impairments (from no light sensitivity to moderate partial sight in both eyes) was sufficient to yield a wide-ranging performance dataset. VIPs with a broad spectrum of walking speeds were included, thus allowing for clearly differentiable characteristics in every pass.

Larger group sizes should be explored in future work as the maximum unidirectional group size of seven (and 14 in opposing flows) may not have been sufficient to create realistic densities in all scenarios. This is especially the case in the widest section (section 3) of the environment utilised within this experimentation. Indeed, VIP behaviour primarily limited group performance, and the threshold for which density became the limiting factor was not found in these scenarios as a consequence of restricted group size.

The instructions given to participants, in retrospect, may be improved; it was felt that certain participants did not consistently react to the 'restricted' or 'unrestricted' instruction. Some participants understood an unrestricted pass to be one where they must traverse the platform as quickly as possible, competing with one another and engaging in aggressive overtaking measurers wherever possible. In contrast, others understood this to be an instruction to simply move freely, rather than quickly, and to only overtake if necessary. This misunderstanding motivated inconsistencies within NSP-VIP interactions, where some overtook the VIP while others remained behind the VIP, physically guiding the VIP in such instances.

Future work including unrestricted and restricted conditions should therefore consider a more comprehensive brief for participants to ensure their equal understanding of the experiment's objectives. Arguably, however, the inconsistent VIP-NSP interactions driven by participants' own interpretations of the flow condition remains realistic, especially as Sorensen and Dederich (2015) noted similar instances of group members assisting one another in evacuations involving VIPs.

Finally, future work should now utilise the empirical foundations of this experimentation to determine their manifestations in realistic settings. For instance, this experimentation was not able to identify how performance may change on varying the angle of opposing flows (such as the meeting of opposing groups at right-angled intersections), or from environmental augmentations and the use of different mobility aids (such as guide dogs). Indeed, as described in Chapter 6, factors such as reduced environmental illumination impact the visual function and mobility performance of certain VIPs, thus potentially altering their interactions with crowds in these settings.

Notwithstanding these limitations, this experimentation was successful in deriving individual and group behaviours not realised in prior studies, made possible by combining a controlled set of environmental parameters and group conditions. Moving forward, VIP behaviours in

crowds should be carefully considered in relevant future work. This is especially considering the improvements in VIP performance induced by group conditions that contradict the hypotheses arising from literature review.

6. Current Methods of Augmenting the Mobility Performance of Visually Impaired People

Chapters 3 and 6 provide a novel understanding of the causal factors of mobility capacity. Chapter 6 proceeds with a critical literature review of mobility performance and its augmentation. This comprises the environmental and technological factors that the visually impaired person will interact with in realistic settings, forming the next phase of mobility assessment described in Chapter 2. Section 6.1 introduces this chapter and its process. Section 6.2 investigates environmental factors including lighting, contrast and colour, signage, and other multi-sensory interactions. Section 6.3 reviews mobility aids, their categorisation, and the challenges that they should overcome to be effective. Section 6.4 concludes the chapter and introduces the integration of these findings into the requirements framework in Chapter 7.

6.1. Importance of Considering Environment Characteristics and Mobility Aids

6.1.1. Environment Characteristics

Observing the mobility capacity of visually impaired people was the first phase of the holistic assessment and development of visually impaired mobility. The environments in which they mobilise, and any mobility tools employed to augment this are now considered (Norgate, 2012; Strickfaden & Devlieger, 2011). This is as built environments typically present a complex visual and auditory field, characterised by non-standardised illumination, contrast, and signage. This also includes soundscapes that may hinder the audibility of auditory cues, such as public announcements in transit stations (Sanchez & Maureira, 2007). The built environment is defined by Tester (2009) as ‘spaces such as buildings and streets that are deliberately constructed as well as outdoor spaces that are altered in some way by human activity’ (p. 1591).

Indeed, as described by Sanchez and Maureira (2007), the visual and auditory fields presented by these environments form an important part of the user’s knowledge of that environment. This correlates with the user’s confidence and, ultimately, mobility within it. For instance, in a transit station, the transport user must acquire sufficient knowledge of the transport network to effectively use it. This begins with an understanding of key network features, such as train lines and stations, and extends to specific characteristics of the local network, such as the transit station name, its position within the network, and the lines that serve it. Transit station illumination, signage, and public announcements are principal mediums used to deliver the information necessary to achieve this. These are therefore typically governed in their design to meet certain usability standards (ANEC, 2010).

In the instance of metro stations in London, for example, these standards are set by the transport operator, Transport for London (TfL), following the overarching standards for rail accessibility enforced by the Office of Rail and Road (ORR) (Transport for London, 2016; Great Britain. Office of Rail and Road, 2010). These design considerations are not limited to transport infrastructure. Building regulations including BS 8300 aim to convey these standards across all aspects of the built environment (British Standards Institution, 2018). Other modifications to aid mobility impaired people in built environments, such as step-free access (Transport for London, 2017), are outside of the scope of this study. Environmental elements including illumination, contrast, and tactile feedback remain applicable here, albeit with uncertain significance or controllability.

6.1.2. Mobility Aids

In addition to environmental augmentation, the visually impaired user may employ mobility tools to assist their ability to detect obstacles, navigate their environment, or seek information on what is around them (Real & Araujo, 2019). Several different types of mobility tool exist, from the standard white cane (Strong, 2009) and guide dog (Refson et al., 1999), to solutions employing sensors and haptic or auditory feedback, such as the Sonic Torch (Kay, 1964), the vOICe (Meijer, 1992), and UltraCane (UltraCane, 2022). These devices vary in purpose and formfactor, with some opting to only provide the user with object preview and others combining object preview and navigation capabilities (Real & Araujo, 2019; Feghali et al., 2021). Additionally, the environments in which each effectively operates varies between device, with outdoor and indoor environments presenting distinctly different user and system requirements (Bradley & Dunlop, 2004; Simões et al., 2020).

As such, it is critical to investigate these mobility tools in detail, considering their historical evolution, current implementations, and the user requirements derived throughout this timeline. Indeed, development of these tools through well-understood user requirements presents an opportunity to directly influence an individual's mobility through several environments (Simões et al., 2020). Such may often be more cost-effective and scalable than altering individual environments where different standards already operate (British Standards Institution, 2018; Office of Rail and Road, 2010).

6.2. Environmental Characteristics and Associated Mobility Outcomes

6.2.1. Lighting and its Illuminance Level and Colour Temperature

An environment's lighting is its most fundamental characteristic given that an individual's visual capacity is a function of light and its perception (Corn & Erin, 2010). Lightning comprises of two characteristics considered when investigating human perception, namely illuminance and Correlated Colour Temperature (CCT), often shortened to colour temperature (Shamsul et al., 2013). Illuminance describes the amount of light falling onto a given area and can be perceived as brightness. The CCT of a light source is the temperature of an ideal black-body radiator radiating light that is similar in colour to that of the light source. This can be perceived as the light's colour, with warmer lighting tending towards yellow and cooler lighting tending towards blue. Both illuminance and CCT can be quantified through units of lux (lx) and kelvins (K), respectively.

The definition of adequate lighting for general use in different operational scenarios is guided through regional standards. Examples from the United Kingdom include the Rail Vehicle Accessibility Regulations (RVAR 2010) for non-interoperable railways, to BS 8300 for the design of an accessible and inclusive built environment (Great Britain. Office of Rail and Road, 2010; British Standards Institution, 2018). Research has also been conducted to demonstrate the impacts of lighting on visually impaired mobility (Wright et al., 1999; Black et al., 1997; Boyce et al., 1999d; FSEG, 2018; Feghali, 2018). Note that these studies have primarily investigated illumination rather than CCT, leaving uncertainty on how CCT affects cognitive processes (Yang & Jeon, 2020) and visually impaired mobility (Katemake et al., 2019).

An early investigations of lighting augmentation for visually impaired mobility is a study conducted by Wright et al. (1999) at the BRE testing facility. Here, the impacts of six differently illuminated wayfinding systems on the ability of a visually impaired individual to evacuate an office building were determined. 30 visually impaired and 6 normally sighted participants were tested. The visual impairments observed were RP, macular degeneration, glaucoma, and diabetic retinopathy. The testing environment featured a small office space which the participant first needed to exit by finding a door. This led to a stairwell landing where the participant would have to descend a set of stairs, then exit via a corridor. A description of each of the wayfinding systems used is shown in Table 6.1 below.

Wayfinding System	**Description**	**Avg. Luminosity (lx)**
Photoluminescent wayfinding system	Green photoluminescent tracks (100 mm width) fixed on floor or skirting board to both sides of corridors. Strips (50 mm wide) placed on walls.	<0.005
Overhead emergency lighting	Five 4 W fluorescent luminaires mounted on the ceiling and one high on the wall at the bottom of the stairs.	1
Normal lighting	Typical ceiling-mounted lamps primarily illuminating the centre of pathways.	70
Electroluminescent wayfinding system	Pair of blue-green electroluminescent strips placed on both sides of corridors, stairs, and on wall between office and landing.	<1
LED wayfinding system	Positioned similarly to electroluminescent system, also including pictorial and arrow-shaped LED-lit signage.	<10
Mini incandescent wayfinding system	Incandescent tracks placed along corridors and stairs. No other signage. Photoluminescent system provided negligible illuminance.	<5

Table 6.1: Overview of wayfinding systems used by Wright et al. (1999).

Appendix N details the walking speeds referenced in this analysis. Firstly, a greater overall walking speed was found in the reverse pass relative to the forward pass. This corroborates the effects of a repeated pass, and the enhanced knowledge and cognitive map developed by the individual (discussed in Chapter 3). In considering the performance of each wayfinding system regardless of pass, normal lighting was found to be the most effective wayfinding solution while also providing significantly greater luminance relative to the other systems tested. This was followed by the electroluminescent and LED systems, the mini-incandescent and overhead emergency lighting systems and, finally, the photoluminescent strips.

Additionally, participants stated that the photoluminescent system, which presented the least luminance, was the most difficult to use. This suggests that brighter and more direct sources of light are more useful for visually impaired wayfinding. Such a conclusion is reaffirmed by the visual impairments tested. The majority of test subjects suffered from RP, a condition that causes reduced contrast and light sensitivity (Openshaw et al., 2008).

A similar conclusion is observed in a study by Feghali (2018). Here, 4 visually impaired participants and 1 normally sighted participant were asked to traverse a platform at PAMELA under different environmental illuminations. Four luminance levels were tested, ranging from

256 lx to 4 lx. The visual impairments tested were Glaucoma, LCA, and RP. The time to traverse the platform for the normally sighted participant was consistent regardless of light level, whereas the performance of all the visually impaired participants tested reduced as the environmental illumination reduced. The reduction in performance varied in magnitude across each participant and light level. Notably, performance was significantly different in the two participants with RP, demonstrating that mobility performance can be widely varied even within identical diagnosis of visual impairment. Reductions in mobility were most drastic as the light level fell below 64 lx.

The study was novel in that the platform the participants traversed featured three different and controlled subsections, similar to the platform design in the MeiraGTx gene therapy experimental methodology (Rubin et al., 2010; Kumaran, 2018). These sections tested straight-line walking speed (baseline), larger obstacle detection through a maze section created with large barriers, and smaller obstacle detection through foam blocks randomly spaced apart that must be stepped over.

It was noted that decreasing illumination most affected smaller obstacle detection, though performance across both of the other sections was also detrimentally impacted. As illumination decreased further, performance across all sections became significantly worse for the participants with the most severely impaired vision. Here, the overall environmental illumination fell below a threshold of usability for any spatial orientation.

Indeed, this was exemplified by Feghali (2018), where the illumination in Old Street Station in London was found to be significantly below the standards set within the local transport authority's station design idioms. Problematically, this occurred on certain staircases and corridors. The station is a key transport hub for visually impaired patients travelling to Moorfields Eye Hospital and therefore suggests that a station with greater visually impaired usage remains insufficiently adapted to improve mobility. This was confirmed by 10 out of 12 surveyed visually impaired patients at Moorfields Eye Hospital that described insufficient lighting at the station, Moreover, all 12 patients expressed that the station could only benefit from more illumination.

A failing of this study was the unsatisfactory number of participants involved within the experimental phase. The resulting data cannot be used to derive a reliable approximation of how different environmental illuminations impact mobility across specific visual impairments. Feghali (2018) tested one eye at a time for each participant, leading to several repeated runs in an attempt to collect a more statistically significant data set. This presented a novel comparison of how each eye differently impacted each participant's cognitive state and mobility.

The translation of these findings into real-world mobility is limited given that the performance achieved via the use of both eyes is not a simple function of the performance achieved via each individual eye (Chung et al., 2017). Mobility testing to correlate visual impairment with mobility performance should therefore consider the interactions of both eyes where individual eyes are being tested.

A larger study preceding Feghali (2018) that investigated the impact of illumination on visually impaired mobility is that by Black et al. (1997). This study only investigated participants with RP. Black et al. (1997) recognises the need for an empirical environment for mobility testing, and one that is not as perceivably 'low-risk' to the participant as a controlled laboratory setting.

This study was also more comprehensive in its data collection, measuring visual acuity, contrast sensitivity, and average visual field extent to assess each participant's visual function. This was in conjunction with PPWS and error scores to assess functional performance within the employed indoor obstacle course. 10 participants with RP and nine age-matched control subjects participated in the study. However, only two illumination levels were tested, a lower level (25-41 lx) and a higher level (500-570 lx).

It was found that visual field was the strongest predictor of mobility. Participants with RP presented reduced walking speeds and greater number of errors than normally sighted participants, more so under the lower illumination level. The presence of a high-power spotlight to induce disability glare suggests that point sources of light should be controlled to reduce risk to mobility performance. However, given that only two significantly varied illumination levels were tested in comparison to Wright et al. (1999) and Feghali (2018), it remains difficult to interpolate and predict the variance of visually impaired mobility across specific illumination levels.

As to CCT, research does not typically recognise this characteristic of lighting in the context of mobility. Rather, studies investigating CCT do so to investigate cognitive processes, including productivity and mood, in settings such as classrooms (Yang & Jeon, 2020) and office spaces (Ru, 2019), or to assess general perception (Harrington, 1954; Ju et al., 2012; Fotios & Levermore, 1997), or to investigate impact on visual function (Navvab, 2001; Boyce et al., 2003). Katemake et al. (2019) also conducted the novel experimentation of illumination and CCT on visually impaired mobility.

Firstly, it is apparent that studies investigating the effects of CCT used few increments between the range of CCT tested. Moreover, studies experimented with CCT values at different illuminations, although the range and increments of illuminations observed were likewise limited. However, there is good consistency between studies which allows for comparison between them. For example, three of the most recent studies investigating cognitive performance impact from CCT are described by the following table (Table 6.2). Experiment 1 investigating illumination and CCT from the study by Katemake et al. (2019) is included as a point of comparison.

Study	CCT (K)	Illumination (lx)	Test Sample	Environment
(Yang & Jeon, 2020)	3000, 4000, 5700	650, 1050	60 healthy students (no visual impairment)	University classroom
(Ru, 2019)	3000, 6500	100, 1000	57 healthy students (no visual impairment)	Lab-simulated office environment
(Lan, 2020)	3000, 6000	300, 2000	24 healthy students (no visual impairment)	Ordinary office room
Katemake et al. (2019) – Experiment 1	3000, 6500	10, 100, 1000	50 low vision and elderly participants	Mobility walk course with random obstacles

Table 6.2: Comparing illuminance, CCT, test sample, and environment in a selection of related studies.

CCTs ranging from 3000 K to 6500 K are utilised, with most studies opting to test two extremes. Yang & Jeon (2020) tests three values, determining the existence of an optimal CCT that may lie between extreme values. Such is a practice that other studies did not consider. Moreover, while this range of tested CCTs lies within most indoor lighting ranges, not all lighting operational scenarios may be represented. For instance, 1800 K-2400 K is typical of sunrise/sunset and incandescent lamps, while 15,000 K-27,000 K can be achieved by daylight under clear skies. Illuminations tested are far more variable. Although, Katemake et al. (2019) employs a wide range from 10 lx to 1000 lx that is likely to test a broad spectrum of visual ability.

Katemake et al. (2019) is the only study found to have investigated illuminance and CCT on visually impaired mobility. While the test sample observed appears to be statistically significant on first assessment (n=50 low vision, n=13 elderly), it becomes evident that there lie some significant shortcomings. Table 6.3 describes this test sample as seen in Katemake et al. (2019). Firstly, the classification of the test sample does not adequately discretise visual function. Instead, participants are classed per eye with terms as 'blurred/blurred' or 'blurred/blind' vision. Visual impairments known to affect mobility under illuminances as low as 10 lx are therefore undeciphered. It is unknown as to whether any of the participations had conditions such as retinal dystrophy that are likely to affect mobility under these test conditions.

Group	Description	No. of Participants (n)
1	Low Vision – blurred/blurred	24
2	Low Vision – blind/blurred	8
2	Low Vision – blurred/blind	9
-	Low Vision – narrow visual field/blind	3
-	Low Vision – narrow visual field/blurred	1
-	Low Vision – blurred/narrow visual field	1
-	Low Vision – narrow visual field/narrow visual field	1
-	Low Vision – central blind/central blind	1
-	Low Vision – blurred/central blind	2
3	Elderly – with narrow visual field/blind glasses	7
4	Elderly – with blurred/blind glasses	6
5	Elderly – without narrow visual field/blind glasses	7
6	Elderly – without blurred/blind glasses	6

Table 6.3: Experimental sample in experiment 1 in Katemake et al. (2019).

Group 1 and 2 consisted of some of the low vision members. Other low vision members remained ungrouped as each had no other similarly visually impaired member, according to the study's classification. The elderly group comprised of 13 members. Group 3 and 4 involved 7 members wearing narrow visual field/blind vision simulation glasses and 6 members wearing blurred/blind glasses, respectively. Testing with and without vision simulation glasses does allow for an understanding of the glasses' impact. However. it would not substitute the extensive psychological characteristics associated with visual impairment. Additionally, the characteristics between participants were so different and the groups so small as to diminish statistical significance.

Participants were asked to individually traverse a mobility walk course with obstacles. Time (walking speed) and collisions with obstacles (contacts) were recorded as mobility outcome measures. The six settings tested were 1000 lx/6500 K, 1000 lx/3000 K, 100 lx/6500 K, 100

lx/3000 K, 10 lx/6500 K, 10 lx/3000 K, with a seventh test involving only natural lighting (LEDs turned off) at 6500 K. This spread should have presented significant mobility differences when considering the low illuminations tested and comparable findings from research including Rubin et al. (2010) and Black et al. (1997). However, and unexpectedly, Katemake et al. (1997) found no mobility differences in Group 1, 2, and 3 in all tests. This is considering both illuminance and CCT, individually and in conjunction.

Moreover, results from Group 4 showed a continuous increase in mean walking speed as illumination decreased, a unique finding that is contrary to expectations. Groups 5 and 6, tested only under 1000 lx/6500 K with LEDs turned off, presented no significant difference in walking speed. Finally, the average walking speeds of the elderly were greater than those of the low vision groups. The conflicting findings presented by Katemake et al. (2019) and shortcomings in testing methodology necessitate further research to understand the combined impact of illumination and CCT on visually impaired mobility.

Yang & Jeon (2020) found that, in a university classroom, higher CCT led to the reporting of an increased sense of brightness. Other studies investigating CCT and brightness perception corroborate that higher CCT is correlated with greater brightness perception (Harrington, 1954; Ju et al., 2012; Fotios & Levermore, 1997). Such could translate to improved acuity, found in a study of 101 young adults by Navvab (2001) where reading and letter acuity were notably improved at 6500 K in comparison to 3500 K. This is affirmed by Boyce et al. (2003) where participants' speed and accuracy in the performance of an achromatic visual task was much improved at 6500 K in comparison to 3500 K. It was explanation that visual performance could be benefited by light sources producing smaller pupil sizes at similar illuminances.

Cognitive effects were found by Lan (2020) where mood and creativity in 24 healthy students were investigated through completing questionnaires, creative and analytic tasks, and analysis of melatonin concentration. While no significant difference in melatonin concentration was observed, highest positive mood was recorded at high illuminance-high CCT (2000 lx, 6000 K) and low illuminance-low CCT (300 lx, 3000 K), and lowest positive mood at high illuminance-low CCT (2000 lx, 3000 K).

The preceding studies do not include low illumination levels as those experienced by visually impaired individuals in studies such as Feghali (2018), Black et al. (1997), and Rubin et al. (2010). The reliable application of these findings to a visually impaired individual is therefore uncertain where lower illuminance levels are likely to reduce mood and create significant cognitive stress. However, given both the physiological and psychological effects of increasing CCT, it is hypothesised that higher CCT would positively influences mobility performance. This is especially considering wayfinding tasks engaging visual acuity such as reading signage. Additionally, an increased sense of brightness and alertness (Ru, 2019) while maintaining good lighting comfort can be obtained in CCT. That is, if carefully optimised and limited in consideration to glare (Yang & Jeon, 2020).

6.2.2. Contrast and Colour

Contrast and colours perceived by the user are dictated by the intrinsic colours and materials used within their environment. This is also a function of lighting: contrast is a ratio of maximum

(L_{max}) and minimum (L_{min}) luminance or reflectance between two elements, surfaces or objects, generically described as follows:

$$Contrast = \frac{L_{max} - L_{min}}{L_{max}}$$

As such, contrast can vary between a maximal value of 1 when L_{min} is negligible, or 0 as L_{min} approaches L_{max}. Determining visibility through contrast measurement must always simultaneously consider illumination. For instance, signage with black test (L_{min}) on a white background (L_{max}) would yield maximal contrast but be imperceptible if placed under poor or no illumination (Arditi, 2005). To similar effect, environments with high illumination but no distinction between minimum and maximum surface luminance would yield poor perceptibility (such as a white sheet of paper against a white wall),

In conjunction with light reflectance, colour perception can be described by hue (the attribute of which a colour is discernible as blue, red, and so forth) and chroma (the colour's intensity). Consideration of each is particularly important as increases in one parameter have been shown to lead to perceived increases in others (Fairchild, 2013). In addition to losses in perceived luminosity, different visual diseases cause colour vision defects in perceived hue and chroma (described in Chapter 2). Environments should therefore consider each parameter of colour contrast, as detailed by Arditi and Knoblauch (1994):

1. Luminance and reflective contrast must first be maximised. This allows colours closer to white and black to contrast more effectively given the strong relationship between reflectance and perceived lightness.
2. The hue scale-position of colours should be considered to maximise contrast in diseases causing concomitant reductions in hue and chroma sensitivity. Particularly, Arditi and Knoblauch (1994) suggest contrasting dark colours from hue scale extremes with light colours from the mid-scale, avoiding contrasting dark colours from the mid-scale with light colours from the scale extremes.
3. The use of colours against achromatic backgrounds should be avoided as colour vision deficiencies could cause a loss of saturation, resulting in both surfaces appearing achromatic and reducing perceived contrast.
4. Hues that are closely grouped on the hue scale should not be utilised for contrast given reductions in hue sensitivity and discretisation ability in colour vision deficiencies.
5. Finally, colours of low chroma and similar lightness present poor perceivable contrast as, similarly to (3), they may be perceived as achromatic colours of similar lightness. Their use for contrast should therefore also be avoided.

Beyond visual perception, Boucart et al. (2008) demonstrated the cognitive advantage facilitated by using colour. Here, 15 participants with AMD were able detect objects more clearly when colour association was used in place of an achromatic image. 11 normally sighted participants performed equally well on both coloured and achromatic scenes. Boucart et al. (2008) therefore states:

> 'Our study shows that people with low vision are able to rapidly categorize objects and faces with a performance highly above chance even at short exposure times and even embedded in scenes. The facilitated performance observed for coloured as compared to achromatic photographs, and for isolated objects than for objects in scenes, in

> participants with low vision suggests that rehabilitation procedures, technical devices, and magazines for people with low vision should use spatial properties that facilitate image segmentation like coloured surfaces, enhanced contours, and increased spacing between target information and flankers or background.'

A limitation of this study is that only participants with AMD were involved, thus also dictating an older sample. The sample had an average age of 80.2 years and 77 years for the impaired and normally sighted group, respectively. As with Arditi and Knoblauch (1994), these results primarily correlate colour contrast and object detection rather than determining actual functional performance in mobility scenarios. However, these findings remain important as current environmental adaptations operate on an object-by-object basis, rather than sweeping colour contrast requirements per environment (British Standards Institution, 2018; ANED, 2013).

Intuitive selection of different hues and chromas can therefore improve performance in both perceptive and cognitive functions, especially as visual impairment is unlikely to completely diminish these functions. This is supported by collective colour vision research finding anomalous trichromacy and dichromacy to be the most common colour vision defects, with monochromacy being very rare (Simunovic, 2009; Sharpe et al., 1999; Went & Pronk, 1985; Judd, 1943).

Light reflectance contrast is well understood and available in practical implementation through accessibility standards including BS 8300, RVAR, and TfL's station design idioms. Reference is made to 'good' contrast across several environmental categories, including walking surfaces, walls, grab poles, signage, and so forth (British Standards Institution, 2018; Great Britain. Office of Rail and Road, 2010; Transport for London, 2016). However, the specification of good contrast excludes hue and chroma, especially in considering people with low vision.

This is primarily seen in BS 8300-2018, a critical instrument serving as an overarching standard across the built environment in the United Kingdom. BS 8300 states (British Standards Institution, 2018):

> 'For people with good vision, differences in hue (the nature of the colour) or chroma (the intensity of the colour) provide adequate visual contrast. Unfortunately, this is not the case for all people who are blind or partially sighted. The main feature of a surface, which appears to be strongly correlated with the ability of people who are blind or partially sighted to identify differences in colour, is the amount of light the surface reflects, or its light reflectance value (LRV).'

Subsequently, measures pertaining to the contrast presented by environments and their elements in BS 8300-2018 solely reference LRV. Shown in Figure 6.1, BS 8300 places 'considerable confidence' in an LRV difference of 30 points or more (the good zone). It is further suggested that illuminance of 200 lux or more may support the differentiation of surfaces presenting an LRV difference of 20 points, the minimum acceptable limit. Defining exacting hue and chroma parameters to improve contrast perception for visually impaired people is outside the scope this thesis. However, future work should rectify this given the disparity between literature and accessibility standards on hue and chroma.

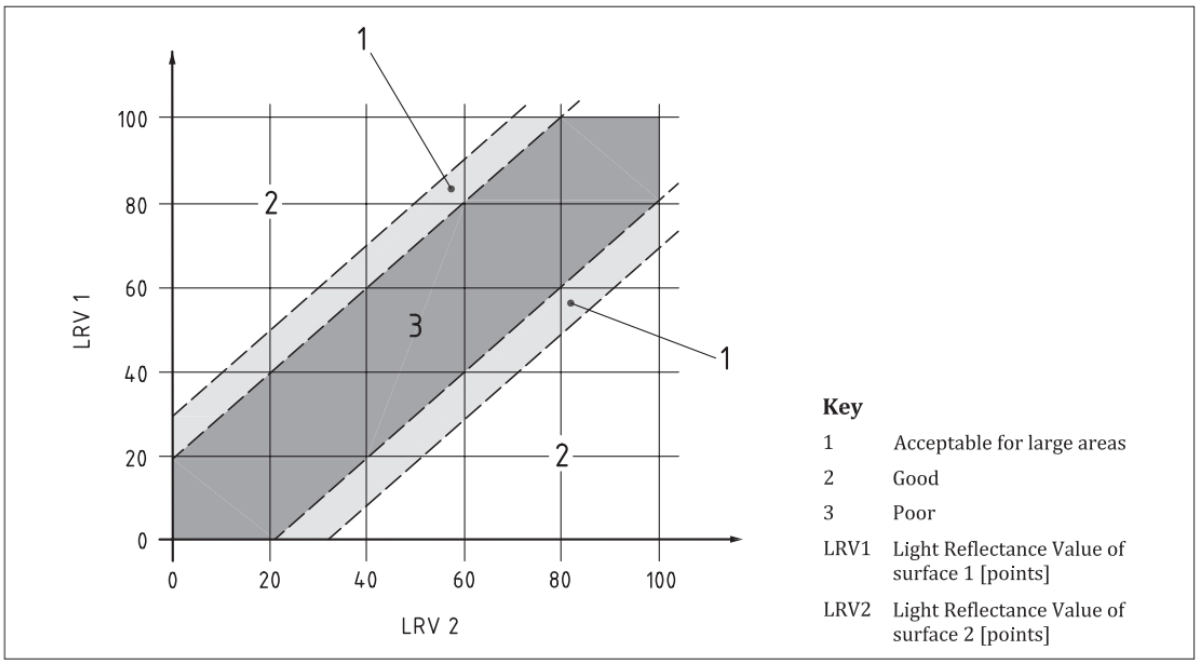


Figure 6.1: Zones of good, acceptable, and poor visual contrast in relation to the LRV of two adjacent surfaces (British Standards Institution, 2018).

Experimentation has been conducted to understand interactions between contrast perception and mobility. Their methodologies can be broadly categorised into one of two groups:

1. The performance of visually impaired people with extensively measured variations in contrast sensitivity (among other visual function) in fixed environments (Marron & Bailey, 1982; Brown et al., 1986; Haymes et al., 1996; Kuyk et al., 1998; Goodrich & Ludt, 2003; Leat & Lovie-Kitchin, 2006).
2. The performance of visually impaired people with limited visual function measurement under variation of environment or object illumination, without consideration of hue or chroma (Black et al., 1997, Wright et al., 1999, Feghali, 2018, Katemake et al., 2019).

Group one and group two have been investigated in sections 3.2.1.1. and 6.2.1, respectively. Additionally, two experiments in Katemake et al. (2019) investigated illuminated edge enhancement in a mobility walk course with obstacles, and the effect of colour contrast enhancement in optimised lighting. The latter experiment is of particular significance given the unavailability of research correlating colour contrast and mobility. It is noted that, in both experiments, Katemake et al. (2019) remains limited in that normally sighted participants wearing binocular visual simulation glasses were used. This negated the enhanced cognitive adaptations possessed by biologically visually impaired individuals, as discussed in Chapter 3.

In the first experiment, the large sample size of 60 participants (of which 15 acted as controls) demonstrates an advantage of recruiting normally sighted participants: the required visual impairments are easier to obtain, albeit with these limitations. The addition of edge lighting was found to primarily reduce orientation and mobility errors, collisions, and walking times in the group with central scotoma. A correlation for the group with tunnel vision could not be obtained. Concentric viewing, as utilised by VIP H in the experiments detailed in Chapter 5, could explain the mechanism for which edge lighting is used by participants with central vision loss. However, the result for the tunnel vision group is surprising. This is as diseases causing tunnel vision, particularly retinal dystrophies, have been found to reduce contrast and luminous

sensitivity (Black et al., 1997, Kumaran et al., 2017, Feghali et al., 2018). The provision of additional luminosity through edge lighting would have been expected to produce improvements in this group as well.

Notably, the group with blurred vision was disadvantaged by edge lightning, both in measured orientation and mobility performance, and reported visual discomfort. This was found to be a result of glare, which may be disabling and detrimental to mobility (Tariq et al., 2007; Black et al., 1997). However, it cannot be concluded that the reduced visual acuity of the blurred vision group was the primary predictor of glare given conflicting findings from Tan et al. (1998).

The relatively high room illumination of 500 lx employed by Katemake et al. (2019) may explain this discrepancy, creating a 'floor' effect: high object illuminations from ambient lighting presided over any edge enhancement (Figure 6.2). Katemake et al. (2019) supports this sentiment by stating that the distribution of light produced by the vertical fluorescent tubes was too diffuse to accentuate object contours. Wright et al. (1999) similarly found normal room lightning to present the greatest performance improvements relative to the individual wayfinding systems tested. Future work should therefore consider stronger edge illumination relative to ambient illumination as the usefulness of edge contrast enhancement cannot be concluded from existing research.



Figure 6.2: High room illumination and edge lighting in Katemake et al. (2019).

The final experiment conducted by Katemake et al. (2019) investigates colour contrast enhancement. This is through a colour contrast perception test and mobility walk course involving 17 and 15 participants, respectively. Only cataract simulation glasses were used throughout, a significant limitation. This is justified by Katemake et al. (2019) in that tunnel vision and age-related macular degeneration (AMD) vision simulation prohibited the perception of enhanced colour contrast in a pre-test. This contrasts findings from Boucart et al. (2008) where AMD-based colour perception was proved as strongly beneficial to performance. This also challenges Arditi and Knoblauch (1994), Simunovic (2009), Sharpe et al. (1999) in discussing the possibility of colour perception in visually impaired people. Uncertainty therefore remains as to the extent of which the vision simulation was reliable.

Notwithstanding this limitation, Katemake et al. (2019) does support findings from Arditi and Knoblauch (1994) in results from the colour perception test. This is that participants were more easily able to distinguish hue pairs further apart on the scale (orange-blue, orange-green, red-

blue) than adjacent hues (orange-yellow, red-yellow, red-orange) as illumination was varied. In the mobility test, the three most distinguishable hue pairs were used to construct the walls and obstacles of a simple walking environment, with participants traversing the course at a reference, and then optimised, illumination level. An average reduction of 36% and 11% was observed in obstacle collision and time taken to complete the course, respectively.

The 'optimisation' element of Katemake et al. (2019) is outside the scope of this thesis but is notable in its method. Here, the optimised illumination was found through calculating and then maximising the difference in measured reflectance of a set colour pair. The optimised illumination may therefore not be functionally optimal in the context of visually impaired perception. This is as maximum reflectance may not necessitate maximal perception, although Arditi and Knoblauch (1994) do suggest light reflectance is a primary contributor.

In summary, conclusive values for optimal contrast in terms of reflectance, hue, and chroma, cannot be produced. This is as existing research is sparse while also employing non-representative samples as a result of inadequate size or tested impairment. However, it can be stated with confidence that augmenting contrast in environments should consider all of reflectance, hue, chroma, and the illumination of the environment itself. A discrepancy therefore arises; design standards typically promote qualitative assertions of contrast through terms such as 'good contrast', or they consider contrast to be a function of light reflectance without further specification of hue or chroma. Katemake et al. (2019), while limited, is a novel study to present the potential performance impacts of well-considered illumination, contrast, and colour. This should therefore be employed as a foundation for future work to better inform these standards.

6.2.3. Signage

Signage is designed as a means of conveying information. In public infrastructure, this includes, but is not limited to, location, wayfinding directions, or an action to operate an environmental feature (Barker & Fraser, 2000). Signs can employ text or other graphical elements such as icons, symbols, or pictures. These elements can be modified in dimension, positioning, and colour to provide enhanced visibility, or to augment the message to be delivered. This is of importance when designing for those with visual impairments and, more specifically, with low vision. Here, some use of visual function can be exploited by signage design to deliver the intended message (Vicente & Sanz, 2008). According to a review of Accessible Signage by the European Association for the Co-ordination of Consumer Representation in Standardisation (ANEC) (2010), the following variable features of signage affecting visibility were quantified in the standards observed:

1. Character size
2. Symbol size
3. Letter form
4. Inter-letter space or kerning
5. Inter-word space
6. Inter-line space or leading
7. Contrast
8. Lighting or illumination
9. Positioning

Arditi (2017) conducted a review of the Americans with Disabilities Act (ADA) Standards for Accessible Design (SFAD) and International Code Council (ICC) signage standards for accessible buildings in the United States. It was found that the standards may meet the needs of those with no remaining vision by stipulating widespread raised-letter and braille use (tactile signage for the blind). However, they failed to serve those with low vision. The standards' reliance on simple physical dimensions for signage was found to be a primary cause of this, especially as those specified did not provide a sufficient evidence base.

For instance, the standards do not account for the fundamental concepts of visual function, such as contrast and visual angle. Rather, character dimensions and spacing is prioritised for poor acuity or tactile use instead. This is true for both types of accessible signage classified by the standards; these are Raised-Visual (RV) signs which feature tactile surfaces for touch deciphering, and Visual-Only (VO) signs which only present flat lettering against the signage surface.

RV and VO sign specifications are summarised in Table 6.4, adapted from the ADA SFAD (United States. Department for Justice, 2010). Here, only the parameter of contrast defines the sign's required visibility for users with low vision resulting from poor contrast sensitivity. Additionally, insufficient information is given as to what defines a light and dark background or text. This leaves margin for subjective judgement. Additionally, a definition of signage luminance was not found in the ADA SDAF, which could drastically impact the visibility of signage in poorly lit settings.

Parameter	RV Signage	VO Signage
Font style	Sans serif, all uppercase	Serif or sans serif, upper-, lower-, or mixed-case
Character height	Between 5/8 in. and 2 in.	5/8 in. to 3 in. based on height from floor
Character stroke thickness	10%-15% of I-height	10%-30% of I-height
Width-to-height ratio	55%-110%	
Character spacing	Min. 1/8 in., Max. 4x stroke width	10% of stroke width to 35% of character height
Contrast	Light characters on a dark background, or dark characters on a light background	
Mounting location	On wall adjacent to door on latch side, with character baseline 48-60 in. above floor	Character baseline minimum 40 in. above floor; otherwise, no mandated location

Table 6.4: RV and VO sign specification summary adapted from ADA SFAD (United States. Department for Justice, 2010).

Similarly, standards in the United Kingdom and the European Union (EU) do not specify sufficiently consistent signage requirements to minimise ambiguity. In the United Kingdom, this is most prevalent in the regulation of transport infrastructure signage, such as the standards defined in the Rail Vehicle Accessibility Regulations (RVAR 2010). Here, signage lettering, including that on passenger information display systems, is required to 'contrast with its background'. Contrast is defined as the 'amount of light reflected' (Great Britain. Office of Rail and Road, 2010). Further detail is not provided as to what constitutes sufficient contrast, and how this differs in environments with varied ambient lighting.

BS 8300-2018 describes signage in greater detail but does not mirror the characteristics or signage categorisation from ADA SFAD (United States. Department for Justice, 2010); BS 8300-2018 requires sans serif typefaces of 'sufficient size for the viewing distance, mixed case (initial capital letter then lower case) lettering that offers a minimum 65 to 70 points contrast in LRV, and a matt surface finish (matt laminate sheets are available to avoid reflection)'. BS 8300-2018 does uniquely suggest that local organisations of disabled people should be informed of alternative routes in case of works or disruption.

Individual transport operators within the United Kingdom may specify additional standards to better uniformity and accessibility across their respective networks. TfL's Station Design Idiom and Signage Manual exemplify this in the London Underground (Transport for London, 2016; Transport for London, 2002). Here, it appears that the limitations of overarching national and international standards manifest on a local scale. This is evident in the London Underground Signage Manual in the definition of the colours and symbols to be used in safety signs, which can present significant challenges to low vision users if poorly implemented. As stated in the document (Transport for London, 2002):

"From 1 April 1996 safety signs have been covered by EC Safety Signs Directive 92/58 EEC, to encourage the standardisation of safety signs by the use of common colours and symbols. This is a legal requirement, and not just London Underground policy. The actual regulations issued – Health & Safety (Safety Signs and Signals) Regulations 1996, are poorly written and have caused considerable confusion. The symbols featured are not an adequate range, and are graphically inconsistent. It does, however, make it clear in the small print, that symbols shown may be adjusted within reason, and that additional symbols may be used, providing they comply with the principles outlined."

The manifestation of accessible signage regulations across EU member states is compiled by the Academic Network of European Disability experts (ANED) (ANED, 2013). The review concluded that the general obligation of national law pertaining to disability, non-discrimination, and accessibility present a broad duty of providing sufficient accessibility and inclusion. There typically exists more detailed technical specifications for the accessibility of the built environment and transport services, where mobility performance deriving from the accessibility of signage is most relevant. However, in the example of accessible signage, as well as in other such goods and services, there is great variance in the specificity of accessibility requirements across each state (ANED, 2013).

This is supplemented by the review of accessible signage standards conducted by ANEC (2010), where significant variations in the requirements of signage features were observed across member states. In the majority of instances, no explanation is given as to how this requirement was derived. Additionally, there exists a divide in standards uptake between the public and private sector, where public sector services are more likely to adhere to these standards (ANED, 2013). When combined with the voluntary nature typical of these standards, it is evident that inconsistency and significant uncertainty remains as to the design and impact of such services as accessible signage.

As a result, limited mobility research on the functional performance of visually impaired people under the interaction of each characteristic of signage is retrieved. This is likely given the numerous characteristics and standards associated with signage. To corroborate this, the existing research on assisting visually impaired people to identify signage has prioritised the

development of mobility aids, rather than modification of the signage itself. This is exemplified by Ezaki et al. (2004) and Foong et al. (2011) in investigating text extraction through image recognition, or OrCam (OrCam, 2022) as a commercially available head-mounted device for auditory object and text feedback. It is therefore recommended that future work investigates the effectiveness of modifying characteristics of signage for visually impaired mobility as the current evidence-base is insufficient for conclusive standards.

Notwithstanding these limitations, guidance for maximising visibility can be generated in intuitively observing common themes across international standards and literature on signage visibility. Firstly, the largest font size should be employed, maximising use of the signage surface area. In applications with lower or mixed-case letters, Arditi (2005) additionally suggests considering the 'x-height' of letters. This characterises the height of most lower-case letters and is an important indicator of legibility. Choice of letter-case may also affect the cognitive processing required for interpretation, and should therefore be selected according to signage purpose (Arditi, 2005; United States. Department for Justice, 2010). In conjunction to height, aspect ratio should be considered, where horizontal expansion improves readability at the cost of horizontal space and print requirements (Arditi et al, 1995).

Stroke should be controlled as to avoid characters being too thin, reducing visibility, or too thick, leading to reduced spacing between them (Arditi, 2005). Arditi et al. (1990) find that fixed character spacing is preferable for small font sizes (or when the acuity limit is reached). The compressed horizontal width and subsequent reduction in eye movement benefits variable spacing in larger fonts. To similar effect, Flom (1991) explains that general increases in spacing are preferable towards the acuity limit, especially as this is how those with low vision are likely to observe signage (Arditi et al., 1990).

Arditi et al. (1997) suggests that filled fonts are more legible to those using outlines. Font appears to contribute to reading performance, especially as font size approaches the acuity limit. This was discovered by Mansfield et al. (1997) where 42 participants with low vision performed better with Courier versus Times in reading acuity, critical print size, and reading speed. Arditi & Cho (2000) suggest that serifs have insignificant impact on performance. Aditi (2005) recommends using familiar, non-decorative fonts while minimising special effects such as shadows.

Finally, illumination and contrast are similarly applicable to signage as in any other objects within an environment (Arditi & Knoblauch, 1994; British Standards Institution, 2018). Therefore, contrast should be increased by primarily maximising light reflectance between signage background and its text. This is followed by the selection of light or dark colours at the spectrum extremes, and combining hues that are as dissimilar as possible.

The Royal National Institute of Blind People (RNIB) (2015) demonstrates a practical implementation of this and suggests that exacting values for optimal contrast remain situationally dependant. These require visual inspection and intuition to achieve optimal results relative to environmental illumination, tint, surface glare, and so forth. Existing signage standards should therefore be taken as minimum standards with opportunity for improvement.

6.2.4. Auditory, Olfactory, and Tactile Interaction

Environmental information acquisition is a multisensory process that extends beyond the use of vision. This is necessary considering the varied nature of visual impairments and the inconsistent effectiveness of visual reference points presented by environments. Auditory, olfactory, and haptic interactions are therefore considered in the assessment of realistic visually impaired mobility, particularly when useful vision is not available (Sanchez & Maureira, 2007; Jenkins et al., 2015; Koutsoklenis & Papadopoulos, 2011a; Koutsoklenis & Papadopoulos, 2011b).

Jenkins et al. (2015) overview several auditory challenges faced by visually impaired people when navigating the built environment, all pertaining to extreme sensory backgrounds. Closed environments with high sound reverberation (such as tunnels) and open spaces with no sound reverberation (such as open fields) diminished the positioning, and thus usefulness, of sound cues. Similarly, objects within an environment producing persistent or sudden loud noises can mask useful auditory reference points, such as at a street crossing. This may result in disorientation and safety risks.

Contrastingly, hybrid vehicles and other vehicles with low sound emittance were found to be difficult to identify. Such is why Acoustic Vehicle Alerting Systems (AVAS) are currently being standardised (Fortino et al., 2016), although the effectiveness of these systems remains to be quantified. This is especially for other quiet vehicles including e-scooters and cyclists where AVAS has yet to be implemented (Fortino et al., 2016; James et al., 2019; Royal National Institute of Blind People, 2020b). Consequently, auditory boundary detection described by Ashmead and Wall (1999) may not be controlled or guaranteed in all environments. Future work is therefore needed to determine the thresholds of useful environmental sound profiles. This is considered in the thematic analysis conducted within this thesis (Chapter 9) in observing the challenges faced by visually impaired people on an environment-by-environment basis.

Koutsoklenis and Papadopoulos (2011a) categorise and prioritise the sounds used by visually impaired people to mobilise in the built environment. It is found that 6 of the 10 most-used sounds were machine-generated (such as cars, buses, and construction works), with the remainder being human sounds (footsteps, people entering and existing places, and children playing), and a natural sound (ocean waves). The sound of cars and traffic is noted as the most important cue, facilitating orientation and aiding the ability to walk in a straight line. This included sounds that would typically be assumed as nuisances (car horn and brake noises). Findings from Jenkins et al. (2015) are therefore confirmed by Koutsoklenis and Papadopoulos (2011a), particularly the criticality of AVAS and its standardisation: quieter machinery, while intended to be more pleasing to their users, detriment their perceptibility by a visually impaired person.

Findings from Koutsoklenis and Papadopoulos (2011a) were obtained through a focus group of 4 blind and 6 partially sighted individuals, questionnaires from 30 blind and 30 partially sighted respondents, followed by structured interviews with 10 blind and 10 partially sighted individuals selected from these respondents. Although visual function was not quantified, a range of O&M abilities and adventitious and congenital visual impairments were chosen, This represents a well-considered and sufficiently-sized experimental sample for good result reliability.

Surprisingly, announcements (such as those used in train stations to indicate the next departure) were not explicitly qualified here. Although, these remain a prevalent and controllable source of auditory information in busy urban environments (Norgate, 2012; Strickfaden & Devlieger, 2011; Great Britain. Department for Transport, 2021). Quinones et al. (2011) affirm that voice announcements on buses and 'talking' crosswalks are information sources depended on by visually impaired people. Feghali (2018) corroborates this in the context of Underground station announcements. Both used user surveys without functional performance testing.

In support of this, the Department for Transport (DfT) (2021) states that 'audible announcements are helpful to most and particularly to vision impaired people. It is essential that there is a significant difference between the level of background noise (ambient noise) and the level of the signal or announcement.' However, no further standard is set as to their frequency and content. Consequently, Feghali (2018) did find that announcements on Underground trains and stations were not consistent, both in frequency and content, through user surveys and practical experimentation at stations. TfL (2017) notes sensory overload as a primary pain point for transport users. Similar to AVAS, announcements are therefore another critical, yet controllable, source of information that could impact visually impaired mobility.

Tactile cues are similar to auditory cues in that they can both be intentional, such as tactile paving and braille signage, or naturally occurring (Jenkins et al., 2015; Great Britain. Department of the Environment, Transport and the Regions, 1998; Quinones et al., 2011). Tactile paving is the controlled modification of walking surfaces to support safety and wayfinding through tactile drop-off, crossing, and hazard sensing. This is a widespread demonstration of tactile environmental augmentation. As in signage standards, tactile paving standards are set by national institutions and vary according to regional socioeconomical factors (Lu et al., 2008).

Lu et al. (2008) conducted a review of tactile paving standards across the United Kingdom, the United States, Japan, and Hong Kong. While not exhaustive, the study serves to highlight the different types and positionings of tactile paving, and the international inconsistencies therein. It was found that the United Kingdom had produced the most advanced standard with six different functions of tactile paving, while Hong Kong, Japan, and the United States had three, two, and one, respectively. Moreover, the visual appearance of tactile paving was found to be different across regions in that yellow was preferred by all but the UK. Here, red was employed for controlled crossings with other colours (listed by lightness, red-green range, and yellow-blue range) specified for other applications according to their contrast with the surrounding paving. Tactile paving types in the United Kingdom are investigated and found to be as follows (Great Britain. Department of the Environment, Transport and the Regions, 1998):

1. Blister surface for pedestrian crossing points.
2. Corduroy hazard warning surface.
3. Platform edge (off-street) warning surface.
4. Platform edge (on-street) warning surface.
5. Segregated shared cycle track/footway surface and central delineator strip.
6. Guidance path surfaces.

The specifications of dimensions and positionings are extensive, although there remain areas of improvement that limit the standard's usefulness in modern engineering applications. The example of refuge islands is particularly pertinent. It is therefore described in depth to highlight

how such a standard may not agree with requirements, or is constrained by the inherent physical dimensions of the environment. Here, the standard specifies that, for refuges less than two metres in depth, the surface should be laid across the full width. Where the refuge is two metres or more in depth, two rows of the tactile surface should be provided. This is displayed in Figure 6.3 (Great Britain. Department of the Environment, Transport and the Regions, 1998).

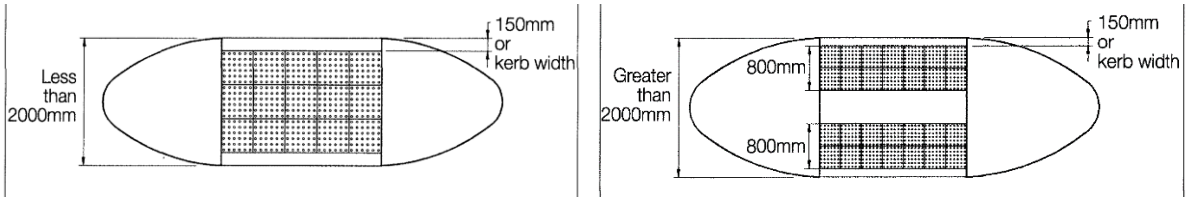


Figure 6.3: Tactile paving standard for refuge islands (Great Britain. Department of the Environment, Transport and the Regions, 1998).

Consequently, the information the visually impaired pedestrian receives is dependent on the depth of the refuge: those with less than 2 m may not be identified as a refuge, but rather the end of the crossing. In practical application, Smithies (2015) states:

> 'Discussions around tactile paving also led two participants to raise issues regarding pedestrian islands at crossings. No identification method exists that allows a blind person to know whether a crossing has a refuge island in the middle of the carriageway. Therefore, when they reach the next set of tactile paving, they have no indication if they are safely on the other side of the road or in the middle of the carriageway.'

This sentiment is augmented through the introduction of modern engineering technology that is not specified in this ageing standard. The exclusion of Platform Screen Doors (PSD) is one such example, and has resulted in uncertainty within this application. This is exemplified by TfL's Elizabeth Line where tactile platform edge (off-street) warning surfaces are not present. Further evidence on the functional performance impacts of this could not be found.

While intended as examples, the challenge of fitting tactile paving according to existing environmental constraints is demonstrated. This is furthered by inherent irregularities in typical walking surfaces; Jenkins et al. (2015) states that uneven walking surfaces such as cracks, bumps, and drop-offs, and irregularly placed obstacles such as low-hanging signs were pain points for visually impaired people. Quinones et al. (2011) explain that tactile irregularities are often possible on familiar routes which leave the visually impaired person susceptible to disorientation and collision. These are categorised into losses of cues (the removal of a familiar landmark), obstacles (construction works, obstructions), and environmental conditions that alter the walking surface (such as rain).

Similarly, Tennoy et al. (2015) stresses that logical, obstacle-free, and smooth walking surfaces with clearly defined drop-offs are ideal, but that these are rarely occurring. While focused on Norwegian Standards, Tennoy et al. (2015) draws parallels to shortcomings found in British standards by attributing this to ageing tactile paving guidance. This leads to irregularities as practitioners implement tactile paving according to assumptions and intuition. However, consistent walking surfaces with natural leading elements are preferrable to surfaces with inconsistent tactile paving. To this effect, the Mayor of London (2021) states that approximately 33% of Network Rail platforms across the UK do not have tactile paving. This

contributes to the significant proportion of people that have a visual impairment that fall of platforms (15%), including one that perished on 26 February 2020.

Jenkins et al. (2015) presented a novel overview of the sensory processes undergone by visually impaired people by way of a cross-sectional survey with 85 respondents from the National Federation of the Blind. This study employed a noteworthy experimental methodology in that survey questions were initially tested and iterated with O&M specialists prior to distribution. Following distribution, three investigators independently reviewed the results and engaged in open discussion with the study coordinators to collate and conclude findings. Lewis et al. (2015) also reviewed findings with subject-matter experts in their derivation of requirements for visually impaired wayfinding. The aid of subject-matter experts is noted and therefore incorporated in the review of requirements in Chapter 7.

Finally, multisensory cues provide context to the environment and are typically only useful for orientation and mobility if they are intentional, or meaningful to an individual (such as a memorable smell from a restaurant, or a bathroom deodoriser) (Jenkins et al., 2015; Gardiner & Perkins, 2005). This is also often dependant on the intensity and proximity of the input, and the individual's residual vision.

Therefore, sensory inputs beyond AVAS, announcements, tactile paving, and other intentional cues are difficult to exhaustively capture and standardise. For instance, a participant surveyed by Jenkins et al. (2015) describes how cold air and traffic noise in a warm building could indicate an open door. The importance of context-specific multisensory cues and their augmentation is therefore considered within this thesis, particularly intentional auditory and tactile cues through personal information delivery. The augmentation of olfactory and miscellaneous cues remains an interesting opportunity for future work. However, these appear to be more useful in facilitating contextualisation rather than orientation and mobility.

6.2.5. Discussion on Environmental Characteristics and their Governing Standards

In summary, it is evident that environmental augmentation is deliberately designed and implemented to assist visually impaired people. This is for both detecting obstacles and achieving improved wayfinding. Standards published globally agree on several principal topics, including lighting, contrast, tactile, and auditory enhancement. However, quantitative guidance beyond qualitative relationships have not been agreed upon. For instance, international standards agree that tactile paving and signage visibility have a positive effect on safety and wayfinding, yet they do not agree on the type of tactile paving and their spacing. This is likewise true for the fonts to be used for optimally visible signage.

The available scientific research explains why such discrepancies exist, including shortcomings of sample sizing, characterisation of visual impairment, and testing environment. These similarly arose in the investigation of mobility capacity. For instance, these shortcomings are observed in studies investigating the relationship between illumination and mobility. Here, Black et al. (1997) and Feghali (2018) determined that lower illumination negatively impacted mobility, although using highly specific or small participant samples at vastly different illumination levels. Standards for visually impaired mobility therefore rely on typically fragmented research without certainty of optimality. The negligence of hue and chroma in BS 8300 demonstrates this: research has shown a positive effect of colour on

visibility, yet this has not translated into actionable recommendations for the optimum hue or chroma in general applications.

The research observed within the preceding literature review primarily relates to specific elements within generic environments. While useful for determining general principles, this cannot determine the extent to which these interact and vary according to specific environments. The state-of-the-art can therefore be summarised as being foundational for generic environmental augmentations. However, it has yet to provide consistent implementation and validation in specific environments.

This surmounts to a literature gap where insufficient research is found to query the challenges of visually impaired people in specific environments. This would allow an understanding of the causal role and prioritisation of augmentations within them. For instance, research is not retrieved to describe the challenges in hospitals versus local clinics, or museums versus public houses. An augmentation such as tactile paving is applicable to these environments, yet it cannot be concluded that this is limiting factor, or optimal solution, for users. This thesis therefore explores the experiences of visually impaired people in specific environments to address this (Chapter 9).

Finally, there exists scenarios in which environmental augmentation is not feasible, particularly in providing sufficient lighting and contrast. Jenkins et al. (2015) illustrate this in a response from a survey respondent, stating 'trees or other buildings that cast a shadow at step downs cause great trouble for those who have minimal sight or light perception only' (p. 8649). Consideration is also given to the physical interactions necessitated by realistic environments, such as traversing stairs. These can overshadow sensory augmentations in users with other mobility impairments, although they lie outside of the scope of this thesis.

For instance, Boyce et al. (1999c) explains that the seemingly simple activity of using a door can be a difficult process for disabled people. This is given the exertion of force required to unlatch and open the door. Particularly, for a wheelchair user, elevated manoeuvrability to pass through the opening without uncontrolled closing or injury is required. To similar effect, TfL (2015a) describes how physical limitations including step-free access continue to hinder the journeys made my users. This results in physical accessibility being a major pain point for customers. The mobility aids utilised by visually impaired people are considered in the following section as these assist the user beyond the limitations of environmental augmentation.

6.3. Mobility Aids and Associated Mobility Outcomes

6.3.1. The Need for ETAs and EOAs

6.3.1.1. Background on the White Cane and Traditional Methods of Improving Individual Mobility

In addition to environmental augmentations, mobility tools for the personal use of visually impaired people have been developed. These can be used across environments and can be designed according to the user's unique abilities and requirements (Real & Araujo, 2019). The most prominent example of such is the long white cane, a tool that is held, swept, or tapped on the ground. This allows for obstacle and drop-off detection, such as kerbs and street furniture, and to act as a symbol of visual impairment to caution nearby pedestrians (Blasch et al., 1996; Strong, 2009).

Strong (2009) explains that the use of a white cane for the purpose of enhancing visually impaired mobility is believed to have existed since 1921. The principals of the white cane have remained unchanged, and studies in the safety and effectiveness of a white cane user's mobility have been conducted. For instance, Kim and Emerson (2018) and Kim et al. (2009) observed the impacts of varying ground surface contact through different cane tips and sweeping technique, respectively. It was found that a tip and sweeping technique with greater ground surface contact was, on average, more effective in detecting obstacles. Additionally, Kim and Emerson (2014) conducted a review of cane technique on obstacle and drop-off detection, noting that cane holding position (Uslan, 1978), height of the cane tip above ground level (Bongers et al., 2002), and ground contact time can impact safety of movement.

Irrespective of cane technique, the white cane can only enhance obstacle detection. It does not alleviate the spatial orientation and wayfinding challenges a visually impaired user may experience (Blasch et al., 1996). The white cane's shortcomings also include limited effectiveness for above ground obstacle detection (La Grow et al, 1997), and that contention remains on effective cane technique according to user ability (Kim and Emerson, 2014). Finally, while the white cane is the most prevalent mobility tool used by visually impaired people, this constitutes a small minority of the visually impaired community. This is exemplified in the United States, where less than 2% of those with a visual impairment use a white cane (Washington State, Department of Services for the Blind, 2019).

Sighted human and dog guides are another classical and prevalent method of aiding visually impaired mobility. Each has well-understood functional performance impacts given their long-standing use for wayfinding, hazard detection, and long-term psychological support (Carter et al., 1986a; Audrestch, 2015; Feghali et al., 2021). Carter et al. (1986a) demonstrated improvements in walking performance when using a sighted guide versus independent performance. Here, visually impaired pedestrians adopted a pace close to that of the sighted guide. Stevens et al. (2003) summarised the critical interface human guides and helpers have in healthcare access for visually impaired people. Bau (1999) and Stevelink et al. (2015) corroborated visually impaired individuals' ultimate dependence on other people for participation in everyday activity. Indeed, the human guide appears to be the 'failsafe' mechanism when independence through self, environmental, and technological development fails.

Refson et al. (1999) observed 82 guide dog owners in Scotland to be healthier and more confident than visually impaired groups without a guide dog. 89% of owners reported that the guide dog brought about a major improvement in their perception of their quality of life. Steffens & Bergler (1998) produced consistent conclusions in semi-structured interviews with 40 guide users in Germany. The guide dog was preferred to the white cane and, to a lesser extent, a human guide. This finding derives from negative bias towards dependence on others in the participant sample. Feelings of greater independence with their guide dog were also reported. Pertinently is the reported companionship and social interaction facilitated by the guide dog. This is a long-term psychological enabler that forms part of the owner's identity (Sanders, 2000).

However, reliance on human or dog guides is not without its limitations. First is an issue of availability; human assistance cannot be guaranteed at all times, and this is typically outside of the visually impaired individual's control (RNIB, 2020a). Training and maintaining a guide

dog are an expensive process, and the successful training of each dog cannot be guaranteed. This arises from variations in temperament and cognitive ability that are naturally occurring in animals (Tomkins et al., 2011). As such, the provision of a guide dog cannot be guaranteed for a visually impaired individual and, if made available, will have a limited working lifetime until retirement from service (Craigon et al., 2017).

Gitlin et al. (1997) and Craigon et al. (2017) describe a physiological and psychological burden of care and responsibility that exists in guide dog ownership, including limitations of places where it is possible to take a dog. The strongly physiological nature of guidance provided by guide dogs involving pulling and rotation can yield soreness of muscles and posture issues. Psychological elements persevere in users receiving unwanted attention from the public, or through feelings of loss and bereavement at retirement of the guide dog.

In addition, determining and regulating the capacity of a living being in their provision of guidance is challenging. This is exemplified in Asher et al. (2013) where a standardized test of behaviour in young dogs was explored to determine viability for training. This holds true for the varied mechanisms employed by human guides which may elevate safety risk (Williams et al., 2014), especially in unpredictable scenarios (such as evacuations) where the performance of an entire group may be lessened (Sorensen & Dederich, 2015; Proulx, 1995).

Williams et al. (2014) provides insight as to why this outcome is different to the good intentions of the human guide. First-hand couple-based observations were conducted with a close companion. It was found that a lack of knowledge hindered human guides' usefulness, particularly in their use of wayfinding language. It was concluded that 'what sighted people think is the right feedback is too often the wrong feedback to give to a person with a visual impairment' (Williams et al., 2014).

The RNIB (2019) sets out guidelines for sighted guides. It suggests that visually impaired people will likely understand the guidance that works best for them when approached by a human guide. This is given the visually impaired person's prior experience of receiving guidance. However, exposure to this guidance by the general public cannot be guaranteed, and research is not found as to how different guiding techniques affect mobility performance.

In summary, human and dog guides are well-established methods of improving the mobility of an individual. However, neither presents a guaranteed availability or consistency of guidance. Furthermore, dependence on human guidance appears vital and often unavoidable when other means of independent mobility fail. Ultimately, however, sustained dependence on other people negates prospects of independent living and is therefore not a preferred or sustainable solution.

A focus has subsequently propagated in research over the past 70 years to develop new individual mobility tools for travel and orientation. This is particularly as the simple white cane was the primary alternative to human and dog guides. Termed Electronic Travel Aids (ETAs) and Electronic Orientation Aids (EOAs), these tools leverage the scientific and technological developments of their time to deliver progressively improving availability and affordability (Real and Araujo, 2019).

6.3.1.2. Introduction to ETAs and EOAs

The primary objectives of an ETA are described by the United States National Research Council (1986), and then reaffirmed by Blasch et al. (2010). These are that the ETA must allow for obstacle detection from ground level to the head height of the user, provide information on the route terrain and drop-offs, detect obstacles bordering the user's path for continuous orientation, and inform the user of the distance and cardinal direction of distant objects of interest. This includes the location of landmarks and information on their identification. Penrod et al. (2009) further discretise ETAs into those that are either primary or secondary. A primary ETA does not require the use of other mobility systems to ensure a user's safety. Whereas, a secondary ETA must be used in conjunction with a long cane, or human or dog guide to ensure the user's safety.

EOAs are primarily designed to assist the user's wayfinding through enhancement of their orientation and ability to navigate. These may include journey planning, information on turning points, and transport connections (Brusnighan, 1989; Strothotte et al., 1996; Feghali et al., 2021). There exists overlap in the definition of ETAs and EOAs as the United States National Research Council (1986) lists landmark information and orientation as an ETA function. Although, ETAs traditionally do not provide wayfinding assistance, while EOAs do not detect a clear path to the objective.

Ultimately, obstacle avoidance and wayfinding are two fundamental requirements. As explained by Feghali et al. (2021), the WeWALK smart cane is capable of ETA and EOA functionality. A new category termed Binary Electronic Mobility Systems (BEMS) is therefore created. BEMS are capable of detecting drop-offs, providing path previews, and using connected smart devices including smartphones to provide EOA data to the device.

Table 6.5. reviews historic ETAs as found through literature review. These ETAs primarily operate through the emittance, reflectance, and processing of energy waves to detect the environmental information within a certain range. The user is then provided with feedback (including auditory or haptic) to notify them of pathways and obstacles. Notably, technology capacity and availability at time of inception appears to be a limitation of these devices: early devices were confined to sonar sensing (primarily ultrasonic), although its slow reflectance speed results in a better ability to determine distance (United States National Research Council, 1986). Accordingly, ETAs are further categorised according to the level of sensing and feedback provided as follows:

- Type I – Detect object presence only with single output sonar waves and are typically 'go-no-go' systems acting as secondary ETAs.
- Type II – Similar to type 1 ETAs but capable of multiple output sonar waves for additional object directionality information.
- Type III – Including all type 1 and 2 functionality with the added capability of extracting and displaying information on the object and surrounding environment.
- Type IV – Including all type 3 functionality with the capability of filtering information according to user preference.

Citation	ETA	Functionality
Kay (1964; 1974)	Sonic Torch (1964) and Sonic Guide (1974)	Type III handheld device (Sonic Torch) or glasses with binaural audio (Sonic Guide) using ultrasound and translating the reflected signal into the audible spectrum for users' interpretation and learning, such as the sound of poles and vegetation.
Russel (1965)	Pathsounder (1965)	Type I chest, neck, or wheelchair mounted device using ultrasound and producing vibrations at 1.83 m and audible beeping at 0.81 m.
Benjamin (1974)	Laser Cane (1974)	Type II cane-based device using optical triangulation with several iterations, the latest being N-2000 with straight, overhead, and downward detection using haptic feedback to notify the user.
Pressey (1977)	Mowat Sensor (1977)	Type I handheld device using ultrasound for object detection at either four or one meter toggleable distances, notifying the user through vibrations of increasing rate according to proximity.
Heyes (1984)	Sonic Pathfinder (1984)	Type IV headband device using ultrasound to detect objects in front or to the side of the user's path, and using auditory feedback through notes on the musical scale analogous to distance with a maximum range of 2.76-3.06 m (highest note) and minimum range of 0.0-0.75 m (lowest note). Each tone represents a distance of approximately 0.3 m of travel with the exception of the lowest tone.
Roentgen et al. (2008)	WalkMate (1993)	Type I handheld or waist-mounted device using U-shaped ultrasonic beams (instead of a traditional cone shape as in the Mowat Sensor and others) of 1.82 m height, 0.7 m width, and 1.83 m range, and using both audio and vibration feedback.

Table 6.5: Summary of Historic ETAs.

The possibility of improved functional performance in visually impaired people with ETAs was demonstrated by Joffee (1987). Here, the Pathsounder was observed in its use for the job retention of a sighted man, and to enable a neurologically impaired teenager to develop outdoor orientation and mobility skills. Kay (1973) summarised findings from questionnaires where 88% of the 94 users and 21 trainers surveyed found the Sonic Guide useful.

Blasch et al. (1989) aimed to understand usage behaviours on a broader scale by conducting a national survey of 298 ETA users. It was found that 140 had used their aid in the last 30 days prior to interview, with only 62 of them carrying their ETA at all times. Additionally, continuous versus selective use was evenly split between users. However, there generally existed positive sentiment towards the use of the ETA for more rapid travel with better obstacle avoidance.

It is noted that this is not reflective of all ETAs; Li (2015) and Roentgen et al. (2008) cite other historical ETAs that are no longer available, or were never made available, to users. For instance, the Sensory 6 (a head or spectacle-mounted device from 1994 providing varying audio feedback), the GuideCane (a cane-based device with ultrasonic sensing and a wheel at its tip to steer the user), and the Bat K Cane (an amalgamation of the Sonic Torch on a cane-based device in 2003). There also likely existed several other smaller projects attempting to replicate this functionality without academic or commercial success.

Indeed, with the exception of the Laser Cane, this extends to the ETAs reviewed in Table 6.5 which were not long-standing and are now historic devices without availability (Li, 2015). The

United States National Research Council (1986) qualified this sentiment in that, by 1985, only 3000 to 3500 devices were estimated to have been sold, and that this is with a great degree of uncertainty given that purchasers of these devices were largely unknown. However, the later study by Blasch et al. (1989) does add perspective as to the division of ETA type among users. At the time of study, 39% used a Mowat Sensor (Type I), 24% a Laser Cane (Type II), 34% a Sonic Guide (Type III), and 3% a Sonic Pathfinder (Type IV).

Correlations between type (advanced functionality), quantifiable usage, and benefit remain uncertain. Interestingly, the laser cane was unique to its counterparts as it principled on the standard white cane, thus allowing it to function as a primary device. It continued to operate as such in the event that its additional functionality was not required (Benjamin, 1974; Blasch et al., 1989). This may have contributed to its relative success, suggesting that visually impaired users may prefer fewer auxiliary devices when mobilising, as also conceptualised through BEMS (Feghali et al., 2021).

Moreover, advanced functionality does not necessitate improved performance. The corresponding information load on the user has been discussed as being potentially counterproductive (La Grow, 1999; Penrod et al, 2009; Feghali et al., 2021). Indeed, although the Sonic Pathfinder was the most advanced ETA type, La Grow (1999) found no marked measurable effect in its use by two participants in a single subject research approach. However, the limited sample size may have contributed to this result.

Another limitation of ETAs is that they are not primarily designed to aid wayfinding and navigation. This is the second fundamental requirement of visually impaired mobility (following obstacle and hazard detection). Devices attempting to surpass ETA functionality therefore saw development from the 1970s and onwards. A primary example of such (among other emerging technology explored in section 6.6.4) was the EOA. EOAs leveraged developments in computer-aided mapping, positioning, and navigation. They equip the user with information about their microscopic and macroscopic environment that was previously not possible with ETAs (Real and Araujo, 2019; Tachi & Komoriya, 1985).

Notably, the transition from ETA to EOA was neither immediate nor distinct, and the reasons for this were twofold. Firstly, there existed the limitation of the technology available at the time of inception. Secondly, the understanding of the user's orientation requirements was insufficient as to how this technology would be best utilised (Real & Araujo, 2019). Subsequently, many early devices iteratively built upon ETAs using similar sensor-sets, but allowed the user to keep better track of their surroundings through computer-modelled mapping (Tachi & Komoriya, 1985). This was exemplified by the NavBelt and GuideCane, a set of ultrasonic sensors attached to a belt and cane formfactor, respectively. These aimed to orientate and guide users around obstacles through providing an acoustic panoramic image of their environment (Shoval et al., 2003).

The GuideCane aimed to address issues arising with delayed user reactions when walking quickly with NavBelt, opting to manoeuvre the user through physically steering their cane using a wheel at its tip. However, both devices were only as capable as their ultrasonic sensors in orientating the user. While they allowed the user some level of localisation beyond that of a typical ETA, they could not provide real-time information on landmarks, transport systems, and the user's absolute position.

These requirements were not prominent within the literature preceding these devices. Real and Araujo (2019) explains that it was only until the broader availability of Global Positioning Systems (GPS) beginning in the 1980s that requirements underwent further research. This was driven by the potentially transformative ability to localise and navigate visually impaired people with new data (Collins, 1985). This introduced the challenge of classifying and delivering digital information in a format that is usable and context appropriate. This was not particular to EOAs, but to any tool attempting to guide a visually impaired user through Positioning, Navigation, and Timing (PNT). This challenge exacerbates as dependence on outdoor navigation systems continues to grow. However, indoor spaces remain a prominent and challenging part of the visually impaired user's journey (Real & Araujo, 2019; Lewis et al., 2015; Elhajj and Feghali. 2020).

6.3.1.3. Introduction to Personal Digital Information Delivery and its Relevance to Mobility

Regardless of intended purpose or system design, human guides, ETAs, and EOAs undertake a similar challenge. This is delivering the 'right' information to the visually impaired user in a form that is both accessible and useable (Williams et al, 2014; Lewis et al., 2015). The delivery of digital information for augmenting visually impaired mobility is therefore an emerging field of research that has received increasing attention. This is particularly given the availability and accessibility of personal handheld devices (Lewis et al., 2015; Real and Araujo, 2019).

The effectiveness of a context-aware indoor navigation system designed for visually impaired people was demonstrated by a study conducted by Sanchez and Maureira (2007) where the mBN (Mobile Blind Navigation) software for pocketPC was developed. Here, desktop software for journey planning and mBN for active wayfinding were tested in a laboratory experiment and in a subway station. A focal point of this research was delivering context-specific information according to the three levels of knowledge described by Sanchez and Maureira (2007). Information on transfer stations, platforms, end stations, consecutive stations, and lines was therefore made available to the user.

Several conclusions are observed. Primarily, planning a journey through the desktop application was beneficial to users with the lowest visual function (blind), signifying the additional planning and reassurance required as useful vision declines. Moreover, pre- and post-experimental surveys allowed users to self-report their ability to use subway features such as tickets offices and turnstiles. An average increase of 20% in scoring was reported in the evaluation of interaction with these elements. As a result, Sanchez and Maureira (2007) noted greater user independence arising from enhanced spatial and time orientation, route selection, and travel via a planned route. It was concluded that the context-specific knowledge provided to users increased competency in interrogating the mBN software for the required information. This benefited the classification and processing of sensory-perceptual information and observation of surroundings.

The sample for the cognitive testing of the mBN system was relatively small and limited in the range of ages and impairments observed. Participants included six students attending the Santa Lucía School for the Blind in Chile, aged 19 to 28, where two were blind and four had residual vision (without further quantification). The results from this study, however, are foundational for the significance of context-aware personal information delivery to visually impaired mobility. A critical review of this research domain is therefore conducted. This aims to expand

the development of visually impaired user requirements for information classification and delivery, particularly in navigation applications.

6.3.2. Classification of Digital Wayfinding Information

6.3.2.1. Fundamental Information Requirements from Early Navigation Experiments

Prior to the development of mBN by Sanchez and Maureira (2007) for indoor use, Strothotte et al. (1996) created one of the earliest EOAs to use GIS and GPS for route planning and navigation. This was named the MoBIC Travel Aid (MoTA). MoTA consisted of two interrelated components, the MoBIC Pre-journey System (MOPS) to assist users in planning journeys and the MoBIC Outdoor System (MOODS) to execute these plans by providing users with orientation and navigation assistance during journeys. As found in Chapter 3, Strothotte et al. (1996) discussed three increasing levels of knowledge for wayfinding. These commence with basic information to ascertain whether or not the user is still on track, followed by detailed information to be selected for inclusion in their journey (such as shop names and nearby landmarks), concluded by transport information such as the nearest bus stop or rail station.

It is inferred that the scale of information grows in terms of distance as the level of knowledge increases. This suggests that the user must primarily understand their immediate surroundings and obstacles, prior to utilising information on distant landmarks and transport links. Information on user journeys can therefore operate on a microscopic and macroscopic level, with effective wayfinding requiring the user to consider information on a mesoscopic level. Sanchez and Maureira (2007) confers with this finding in the context of indoor spaces.

Of note in Strothotte et al. (1996) are the results from the interviews of visually impaired people and mobility trainers. These were used to determine user requirements, as described in Table 6.6. These were tested with 6 participants aged between 25 and 61 in Berlin. Unanimous approval was found for the ability to control the flow of information according to these requirements.

	Essential	**Desirable**	**Ideal**
Route Planning	Basic maps, routes including *Street names* *Distance information* *Known hazards* *Road gradings*	Option to add more detail on several different levels, e.g. *Shops* *Public buildings* *Road crossings* *Public transport* Then more detail concerning these e.g. *Specialist shops* *Nearest Church* *Ticket Office*	Up to date information concerning transient obstacles, e.g. *Roadworks* *Scaffolding* *Diversions*
Interaction Levels	User should dictate the level of detail incorporated in any particular journey plan	User should be able to request area maps or specific routes *Shortest route* *Safest route*	User should be able to edit the journey plan with own comments and memos

Table 6.6: Information requirements found by Strothotte et al. (1996).

Firstly, the importance of each requirement was categorised by Strothotte et al. (1996) as being 'Essential', 'Desirable', or 'Ideal'. No further information was given according to quantitative measures defining each category, and this can therefore be assumed to have been a subjective exercise. Discretization of requirements into those that are 'hard' (essential) and 'soft' (desirable or ideal) is therefore implemented in this thesis' definition of user requirements.

As an essential requirement, Strothotte et al. (1996) found that users must be able to plan the journey prior to travelling. This also included setting the level of detail required within this plan. Street names, distance information, known hazards, and road gradings are classed as essential details. These are reflected in the compilation of user requirements while also considering the soft requirements detailed in Table 6.6. It is concluded that information held by navigation systems for visually impaired people should contain all possible route details, but that this information should be accessible at different levels of detail. For reference, the MoBIC system's inputs, outputs, and their prioritisation are included in Appendix N.

Bradley and Dunlop (2004) conducted a user study to understand the design requirements of context-specific navigation, testing visually impaired people with a novel categorisation of visual function. 15 participants aged 27 to 74 were asked to walk for approximately five minutes to reach each of three predetermined indoor (university building) and outdoor (rich city centre) landmarks. Visually impaired participants were discretised into five with central vision loss (CVL), five with peripheral vision loss (PVL), and five with total vision loss (B), as described by Table 6.7.

Group	**Length of Time Impaired (Years)**					**Mobility Aid**		
	<2	3-7	8-15	>16	Birth	Cane	Guide Dog	None
CVL	0	3	2	0	0	4	0	1
PVL	1	3	1	0	0	2	0	3
B	0	1	1	2	1	2	3	0

Table 6.7: Experimental sample in experiment 1 in Katemake et al. (2019).

The CVL and PVL groups experienced a lower average duration of impairment (with none being impaired for more than 7 years). This contrasted the blind user group where the majority had impairments with a duration of over 7 years, or since birth. The cane represented the most prevalent mobility aid within the group, and only the blind group used guide dogs. While the extent to which these factors affected the study's results is uncertain, it is commendable that the duration of impairment was considered in conjunction with the participant's age. As found in Chapter 3, acquired visual impairments are likely to induce a more substantial impact on the individual's short-term psychological state versus those from birth. The latter allows the individual more time, and likely more training, to cope with their impairment and the information required to do so.

Bradley and Dunlop (2004) found distinct differences in the information requirements of each group and the environmental cues used to orientate and navigate. These prevailed notwithstanding the relatively small sample size and simplistic visual function grouping of the study sample. In the outdoor environment, the B group asked questions about environmental cues not used by others, including side streets, steps, doors, tactile markings, and wind direction. Greater reliance on sound and knowledge of distances was also observed.

The PVL group asked the least questions in fewer categories and detected landmarks through residual vision to orientate, including signs, people, and traffic. This group also possessed significantly more photopic vision than scotopic vision. The CVL group asked more questions on environmental cues, including signs and traffic lights, while using areas of high and low illumination, such as shadows, to orientate.

In the indoor environment, the number of questions increased across all groups, with the most significant increase by the PVL group. Environmental cues were also used in greater proportion by the CVL group. Such was a consequence of the richer and more rapidly changing environment indoors. It is well-understood that participants with increasing visual function face greater dependency on visual reference for knowledge. Findings by Bradley and Dunlop (2004) suggest that, as environments become more dynamic, dependence on external guidance versus tacit knowledge dominates. This is more likely to affect sighted groups than the B group where significantly impaired visual function is less affected by the environment.

These findings correlate with the hierarchy of knowledge derived by Passini et al. (1990), as included in the framework of mobility capacity compiled in this thesis. Particularly, Passini et al. (1990) explains that congenitally blind individuals performed better than those that were adventitiously blind or blindfolded in the control group throughout the majority of cognitive tasks. This was a result of better adaption to the two most advanced phases of the three-phased hierarchy: firstly, pointing to distinctive locations within a journey, finding shortcuts (side streets in this context), and making mental rotations of the journey. Secondly, reproducing the overall layout by discovering spatial organisational principles (distances and the organisation of sounds in this context). Passini et al. (1990) and Bradley and Dunlop (2004) confer in the CVL and PVL groups' respective dependence on residual vision and light sensitivity. This concludes that visual detection was preferred to the elevated spatio-cognitive processing employed by the B group.

It is concluded that information that is meaningful to an individual with one form of visual impairment may be incidental to one with another visual impairment. Systems providing visually impaired people with information should therefore prioritise the provision of the widest-ranging information possible. This allows the user to then filter the information according to their own requirements within the environment in which they operate. Optionally, suggested system information settings for certain types of visual function (such as CVL, PVL, and B) could be employed according to Bradley and Dunlop (2004). However, these must only act as a guide without overriding user preference.

6.3.2.2. Collating and Comparing User Requirements for the Classification of Digital Wayfinding Information

Lewis et al. (2015) presents requirements for visually impaired wayfinding from a literature review and two experimental studies. The first elicits user requirements for mobile location-based technologies to support navigation for blind and partially sighted users, and the second evaluates some prototype tools that emerged from these requirements in a structured experimental setting. Lewis et al. (2015) is explored in further detail given its novelty and relevance to this research. This is especially as the methods underpinning Lewis et al. (2015) considered several studies identified within this thesis, including Strothotte et al. (1996), Bradley and Dunlop (2004), and Wilson et al. (2007).

The first experiment conducted by Lewis et al. (2015) invoked a novel approach to requirements derivation which began with focus groups. The results of which were then validated through consultation with experts within the field. This assisted the prioritisation of each requirement according to the number of participants that suggested it, its corresponding importance to the participant, and the risk to the user if this requirement was not met in a future

assistive system (such as the safety risk associated with not alerting the user to a street crossing). This two-staged approach is noted and subsequently used in the validation of requirements derived throughout this thesis.

The sample group in Lewis et al. (2015) was moderate in size. It comprised 23 people participating in the focus groups where 11 were born with sight loss, 9 developed a sight impairment, and 3 that were sighted. The participants were all aged between 26 and 82 with a mean age of 49.1 years. This suggests a broader representation of the visually impaired population than similar studies such as Walker et al. (2006b). However, this study is not without notable limitations in that no further information was provided on the visual function of participants. Consequently, requirements could not be classified according to visual impairment, as suggested in Bradley and Dunlop (2004). Moreover, participants all identified as independent travellers with an average score of four out of five (with inter-quartile range of one) when asked to rate their experience using technology. The requirements of users that have yet to achieve independent mobility, or that have poorer experience with technology, may therefore not have been represented in this study.

Requirements were reviewed and then discussed with four experts. These included two with technical knowledge and expertise, and two from the RNIB with extensive experience in using or evaluating existing assistive navigational technology (although this experience was not quantified). Notwithstanding these limitations, the requirements derived by Lewis et al. (2015) correspond closely to the research preceding the study. Lewis et al. (2015) therefore marks the first attempt at a consolidated set of requirements for visually impaired navigation. These are summarised for inclusion in the requirements derived through this thesis.

Firstly, users and experts described the essential need for personal information and wayfinding systems to operate in all environments. This includes urban, rural, outdoor, indoor, and public transport settings. Moreover, planning the journey was also deemed essential, as corroborated by Strothotte et al. (1996). Particularly, users gathered information during the planning stage through speaking to people, using the internet, and practising the route. Information was collected during the journey through asking people, environmental cues, auditory reference points, and GPS. Users' own knowledge in landmarks and counting paces supported wayfinding throughout the journey, suggesting that journey planning occurs throughout every phase of the journey (including in different environments).

Perceived accuracy, up to date information, reliability, consistency, and the ability to 'get the user where they want to be' were also essential requirements, as deemed by users and experts in Lewis et al. (2015). These were required for both outdoor and indoor spaces. A gap therefore arises between requirement and technology. Participants' sole selection of GPS as a source of knowledge in Lewis et al. (2015) indicates that they likely do not have a positioning tool for indoor use, where GPS is typically not available (Simões et al., 2020). Feghali et al. (2021) also concludes that a single system has not been able to meet these requirements. This arises from poor data availability, such as public transport information within the user's locale, or insufficient technical capability to position and navigate the user within the space.

Another novel finding by Lewis et al. (2015) is the principle of checkpoints (nodes) towards a final destination. This includes users' desire to walk efficiently between them (tracks) in a straight line. The user journey is therefore comprised of several tracks and nodes where the user must identify the position of each node and traverse the most effective path towards it.

This is while also maintaining an overall orientation of the final destination. As such, Lewis et al. (2015) proposes the following as essential requirements to deliver a system compatible with track and node wayfinding:

- A route overview in list or map form including checkpoints and the final destination.
- Notification of when the user is on/off track and, if off track, how far off track the user is.
- Notification that the user is facing the correct/incorrect direction.
- Notification of nearing and then reaching a checkpoint.
- Distance and estimated time of arrival at next checkpoint.
- Distance to the destination.

Furthermore, informing the user of the total number of checkpoints, the number passed through, and the number remaining were deemed as desirable. Indeed, these requirements are well-aligned with the mesoscopic cognitive mapping conducted by visually impaired people. However, it appears that available navigation systems have yet to adopt this navigation logic (Real & Araujo, 2019). Contrastingly, academic research has prioritised improvements in positioning accuracy and availability rather than user interface design. Such is why Feghali et al. (2021) designed the WeWALK smart cane's navigation logic and user interface to operate on tracks and nodes. The system's design is detailed in Chapter 7 to demonstrate how user requirements are contributed towards the development of a user-facing product.

Finally, Lewis et al. (2015) summarises the critical layers of information necessary for visually impaired wayfinding, complementing those from Strothotte et al. (1996). It is concluded that route previews, obstacle and hazard warnings, nearby point-of-interest scanning, and 'Where Am I?' are essential functionality (Strothotte et al., 1996; Lewis et al., 2015). Lewis et al. (2015) adds path efficiency through keeping the user walking in a straight line as an essential requirement. This is consistent with the principles of effective track and checkpoint navigation. Moreover, a 'free roam' mode allowing the user to explore while keeping them on track is found to be desirable (Lewis et al., 2015). This can be expanded to provide users with exploration information regardless of their motivation, be it freeform or purposeful (Davies et al., 2012).

6.3.3. Interaction with Digital Wayfinding Information

Franklin (1995) explores the shortcomings of language in conveying spatial information in that it requires a complex process. It begins by determining the elements that need to be communicated, temporal structuring of the elements, selection of frames of reference and perspectives, and verbal regularization of spatial relations. Franklin (1995) therefore suggests that the formation of a spatial model from linearly ordered simple expressions can be challenging. This is especially in considering the mission-criticality of the expected task and determining if the user has processed the instruction as intended. In agreement, Tran et al. (2000) found speech beacons harder to localise than non-speech beacons for navigation as users found them to be of lower quality and acceptance. Additionally, Mowbray (1953) explains that, if present, several speech cues at close intervals can be unintelligible or difficult to process, increasing cognitive load.

Walker and Lindsay (2006a) explain that navigation systems for visually impaired people can therefore have unexplored and potentially serious human factors repercussions. Here, an attentionally demanding distractors task on wayfinding performance with an audio-only navigation system was employed. It was found that performance reduced as users' cognitive resources were shifted to the distractor. Klatzky et al. (2007) confirms this by finding that non-speech cues outperformed speech cues in participants' performance of simultaneous cognitive tasks.

When speech is employed, its format should also be considered. Millar (1994) suggests those with visual impairments better understand spatial configurations when identified with respect to their own body. Clock positions should therefore be more useful than words that describe relative positions such as 'near' or 'far' (Sanchez, 2009; Golledge, 1993). Further investigation of spatial audio, speech, and other unconventional displays such as Spearcons, Earcons, and auditory icons (Walker et al., 2013; Loomis et al., 2001; Meyer & Filliat, 2003) is therefore conducted.

Loomis et al. (1998) and Loomis et al. (2001) investigated the use of spatial audio in visually impaired navigation through the development of the Personal Guidance System, a GPS-Based navigation system using spatialised speech. Loomis et al. (2001) summarised the importance of heading, bearing, and course (reviewed in Chapter 3). A challenge to visually impaired navigation was a lack of information on distant landmarks, heading, and self-velocity. Figure 6.4 is the functional system architecture created by Loomis et al. (2001) to address this through a system that the user can interact with.

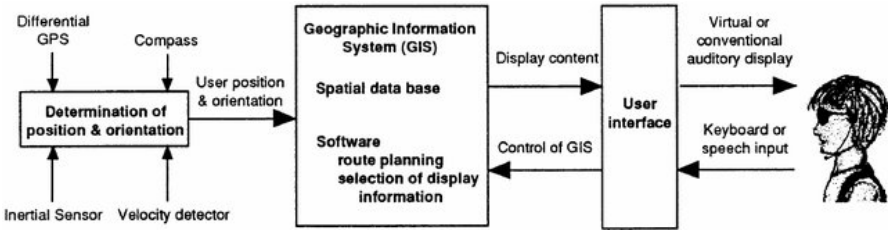


Figure 6.4: Functional system architecture from Loomis et al. (2001).

Of particular interest is the inclusion of inertial sensing and compass data in determining the user's position and orientation. Building on Strothotte et al. (1996), this can support microscopic (detecting immediate route) and macroscopic (finding landmarks) knowledge requirements. The former requirement was tested through experimentation by Loomis et al. (1998) involving 10 blind participants that underwent route guidance through four display modes. Three involved a conventional speech display (left/right, bearing, and no compass), and the fourth involved spatialized (virtual) sound. A large and open grass field was used, and each participant was led along one of four paths of 71 m length, each comprising 9 linear segments defined by 10 waypoints. Figure 6.5 visualises the instructions given to participants according to each mode.

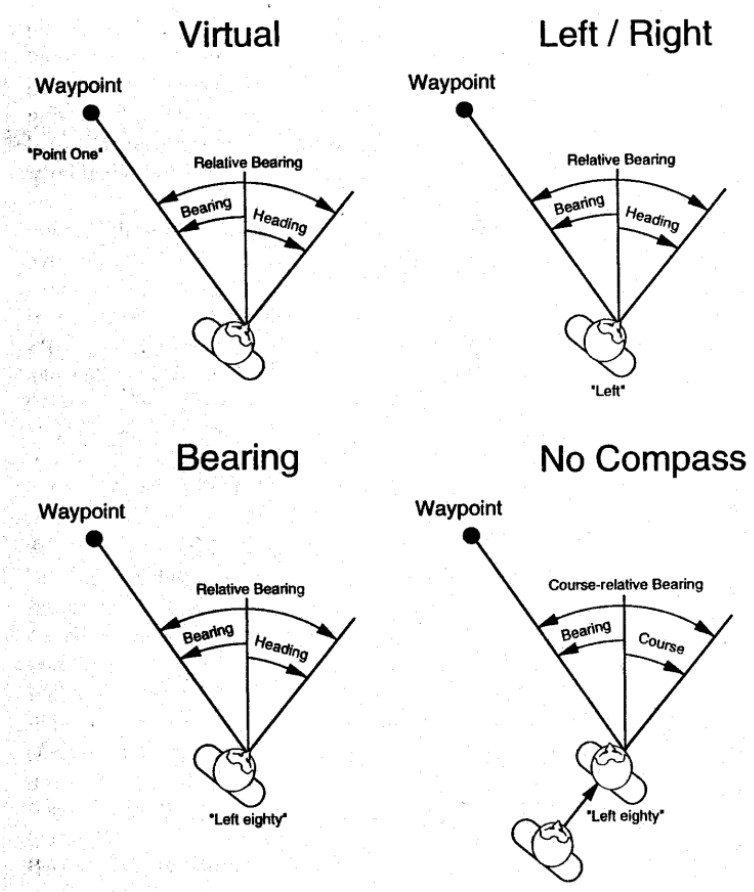


Figure 6.5: Guidance used by participants in Loomis et al. (1998).

In using the time to complete the path as a functional performance measure, Loomis et al. (1998) found the virtual, left/right and bearing modes to be superior to the no compass mode. Spatialised sound also presented the lowest path completion time relative to the speech displays. These findings are significant in that the walking environment was fairly inert (an open space without stated obstacles), the functional performance measure used was valid, and a walking path of good length was employed.

However, no further information was given to the specific visual function and aids used by each participant (which were only described as being blind). This extended to information on the lighting and weather conditions of the outdoor space, which likely would have affected each participant's capacity to detect their path according to their visual function. Irrespectively, the benefit of providing compass data to aid visually impaired navigation is noted. Although, the effectiveness of this according to various impairments or walking environments cannot be derived from Loomis et al. (1998).

Loomis et al. (2001) describes an experiment to define the benefit of spatial sound relative to speech in macroscopic landmark detection. 9 blind participants were guided five times around a square (12.2 m on a side) using virtual beacons at each vertex. Participants received information about the location of three landmarks within the square as they traversed around it, either as spatialised speech (e.g., "statue" projected in stereo sound according to its location) or as bearings (e.g., "statue, 3 o'clock"). The participant's ability to recall the positions of the landmarks was then tested through a sixth pass around the square where no guidance was given. The participant was also asked to describe the location of each landmark according to their

clockface bearing at predetermine locations around the square. Sketch maps were completed following the walking test. In both tests, it was found that there were no statistically reliable differences between each mode, with a mean absolute error of over 40 degrees in the walking test.

In depending on memory recall, Loomis et al. (2001) amplifies the effect of cognitive state described in visually impaired mobility capacity (Chapter 3). Therefore, it cannot be concluded that the poor performance across both tests was a result of the display mode or a limitation of the cognitive ability of the participants tested. This is especially as no further information was given on the participants' visual functions, and no self-reports were collected on their perceptions of the displays or their cognitive state during testing. While Loomis et al. (1998) demonstrated more distinctive results between the spatial and speech displays in microscopic applications, the omission of self-report also limits the conclusions.

Beyond speech and spatial audio, haptic feedback was introduced by Ross and Blasch (2000). This aimed to create a wearable orientation aid for severely visually impaired people who rely on a cane or dog to mobilise, following the suggestions of 20 participants. The interfaces tested were spatial sound beacons, digitised speech, and the tapping interface. This was conducted through analysing the street-crossing performance of 15 subjects with varying visual impairments.

The tapping interface was a novel three by three array of contact speakers mounted to the user's back, triggering according to the direction in which they should travel. In this case, left activated to turn left, centre for straight, and right for turn right. The speech interface presented the user with selectable clock directions or degrees at continuous intervals, and the spatial audio (virtual beacons) projected a stereo bell sound through a stereo headset every 700ms according to the bearing of the user relative to the target. Walking metrics including veering and walking speed were collected. Surveys with participants were also included to determine their perceptions towards each interface.

It was found that the tapping interface was usable by all participants under all conditions. Speech was sometimes confusing and not always usable. The virtual beacons were preferred by some participants but were not usable in very noisy environments or by people with hearing impairments in one or both ears. Moreover, headphones used to transmit stereo audio can mask or obscure environmental sounds around the user that are useful for hazard detection (Strothotte et al., 1996). An ideal interface could therefore be one that combines tactile cues with an improved speech output format, with capacity for spatial audio in scenarios where using stereo sound is appropriate.

This shortcoming of spatial audio was not considered by Loomis et al. (2001), confirming the importance of a mixed methods approach. This includes collecting data from objective measures such as walking metrics, and subjective measures through user surveys, as done by Ross and Blasch (2000). Moreover, Ross and Blasch (2000) explain that performance varied across interfaces when comparing participants to each other. Instead, the best measure of performance was each unique participant's improvement with an interface versus their baseline performance. This concurs with the preference of long-term mobility testing versus short-term testing of several subjects. However, Ross and Blasch (2000) only observed performance in street crossing. This specific scenario may not be representative of interface performance in other scenarios outside street crossing. Tapping interfaces are therefore considered in future

navigation designs given the improvement in performance demonstrated in this specific, yet safety-critical scenario.

Other unconventional displays include Spearcons, Earcons, and auditory icons (Walker et al., 2013; Loomis et al., 2001; Meyer & Filliat, 2003). Earcons are brief musical melody patterns (similar to the bell sound utilised as the spatial audio beacon in Ross and Blasch (2000)). Spearcons are speech phrases that have been sped up, on occasion to an extent where they are no longer recognised as speech. Audio icons are representative real sounds of objects or events. The System for Wearable Audio Navigation (SWAN) devised by Wilson et al. (2007) includes non-speech audio-only outputs for visually impaired navigation in a wearable system with tactile input. SWAN integrates user input, allowing them to author their own GIS inputs for wayfinding, obstacle detection, and situational awareness. This requires GIS infrastructure for geocoding and spatialisation.

While Wilson et al. (2007) does not specify system testing, the system principles on research by Walker et al. (2006b). This finds that simulating a sound and its spatial position using an auditory display is more effective than using speech to describe positional information. For instance, using the sound of trickling water to represent a water fountain (and positioning it in a stereo field) is suggested as being more effective than stating the distance and position of the fountain (in degrees and metres). However, this conclusion was determined from experimentation by Walker et al. (2006b) involving 108 undergraduates from the Georgia Institute of Technology participating for credit (71 men, 37 women). All reported normal or corrected-to-normal vision and hearing. The sample also had a relatively young mean age of 20.2 years and narrow age range of 18-30 years. These findings therefore cannot be assumed to prevail in a representative visually impaired sample.

Notwithstanding limitations in Walker et al. (2006b), participants navigated three maps guided by one of three beacons (pink noise, sonar ping, or a 1000-Hz pure tone). It is noted that overall navigation was very successful regardless of sound. This was the result of practice through more interactions with the beacon sound and capture radius. Small radii reduced overshooting and subsequent time lost in searching for waypoints. A human-scale capture radius (1.5 m) and sonar-like beacon were found to be the optimal combination.

Practice with wayfinding systems has been shown to improve performance in visually impaired individuals, such as through second passes in the wayfinding experiments conducted by Wright et al. (1999). Future work should observe if findings from Walker et al. (2006b) are applicable to visually impaired people. This is especially as practice with a beacon sound was more significant than the sound itself. This is necessary for the safe application of beacon sounds in future navigation systems.

Spearcons were explored by Walker et al. (2013) through five experiments investigating menu navigation efficiency and accuracy. Measures included the learning rate of cues and speech. Spearcons were compared to Text to Speech (TTS) in 2D auditory menus. As in Walker et al. (2006b), all participants were undergraduates (young and narrow age range) that reported normal or corrected-to-normal hearing and vision. The applicability of this research to visually impaired mobility is therefore restricted. Participant samples per experiment were moderate at 9, 11, 24, 39, and 28 undergraduates in experiments 1, 2, 3, 4 and 5, respectively.

It was found that navigation efficiency, accuracy, and learning rate were improved with Spearcons relative to other audio cues. Spearcons showed comparable learnability as normal speech. They also led to better performance than auditory icons and Earcons in two-dimensional menu navigation, resulting from lower per-item cost in menu navigation behaviour. Finally, in comparison to TTS menus, Spearcons led to better performance regardless of added menu item lengths. Indeed, Spearcons should be considered in future navigation system design as an alternative to Earcons and auditory icons. However, there remains significant uncertainty as to their usefulness for visually impaired people in realistic operational scenarios.

Lewis et al. (2015) provides insight into system-level customisation according to users' essential and desirable preferences. The ability to control volume and verbosity, mute the system, select specific landmarks to be notified of, and have both audio and vibration feedback was essential. Additionally, users expressed the essential need for a 'repeat information' function where speech is used for detail, and sound is used for generic information.

However, the types of sounds suggested were only desirable and not essential, demonstrating a user preference for choice. These included bells for arrivals or alarms, and longer tones for warnings and hazards. Notably, lower tones were desirable, but the ability to hear system sounds and ambient sounds without compromise to each was essential. This is corroborated in Strothotte et al. (1996), demonstrating a long-standing requirement notwithstanding developments in audio technology in the 19 years separating each study.

Furthermore, Lewis et al. (2015) lists the inclusion of customisable sounds, a choice of voices, and metric and imperial units as desirable. Indeed, customisation appears to have been favoured by users, more so than a particular method of system interaction. Likewise, this extended to the route requirements. Here, users not only requested several information sources, but also the ability to input their preferred route type based on time of day, terrain, footpaths, congestion, and other streetscape elements.

Minimising path deviation through assisting the user to walk in a straight line is a principal requirement. This is supported by both the experiments conducted in Chapter 5 and the collection of requirements by Lewis et al. (2015). The second study conducted by Lewis et al. (2015) suggests that this may be addressed through different information delivery methods. These include using sound cues to prompt the user that they are off track, on track, or both, and comparing these scenarios to one without sound cues.

Interestingly, Lewis et al. (2015) found no significant differences in straight line performance when observing all users. However, the capacity of each system became more evident on exploring each participant individually. Three participants had residual vision that allowed them to follow a straight line. The experimental sample was restricted in size to only eight participants, and the large standard deviation of walking performances masked system effects.

While exploring each participant's results, it was evident that participants with the least usable vision were most able to stay on the set path. This was when provided with both on and off-track cues. Practice may have confirmed findings given such user responses as 'I was struggling to remember whether left meant go left or I was left of track' (Lewis et al., 2015). Longer-term testing of sound versus no sound scenarios is therefore suggested in future work, employing similar methods to those in Lewis et al. (2015), and Ross and Blasch (2000).

In summary, technology has an opportunity to improve information delivery for visually impaired users. However, the challenge remains in achieving perceptual realism and locational accuracy for route and off-route knowledge. An improvement in performance can be achieved during route guidance with spatial sound given the user's ability to identify the next waypoint along the route. Although, similar performance cannot be guaranteed in facilitating macroscopic knowledge of the surrounding environment. The introduction of Spearcons, Earcons, and audio icons has shown promising results in user interface interaction and navigation performance.

The testing of these systems has primarily involved non-representative experimental samples. Their use as an option in future system designs is suggested, although additional experimentation with visually impaired participants is required to define their usefulness. This includes deriving optimum parameters (sound, frequency, and catchment area), and vulnerabilities and failure modes (such as reducing the user's capacity to hear their environment). Ultimately, providing users with options as to how they interact with the system is as critical as refining each interaction method, be it haptic feedback or spatial sound.

6.3.4. Sensory Substitution and Other Emerging Research to Aid Visually Impaired Mobility

Beyond traditional ETAs and EOAs, the use of sensory substitution to improve mobility has been investigated in research. This is founded on the rationale that the brain can adapt to process deficiencies in vison through the other senses (Bach-y-Rita et al., 1969). This could be for the purpose of object preview, orientation, or both. The differentiator is that, unlike prior approaches that interpret elements of the environment through different sensing, sensory substitution visually captures the environment and translates this image into a format that the user can then interpret (Bach-y-Rita et al., 1969; Meijer, 1992).

This principle was first conceptualised by Collins (1970) through the use of a matrix of haptic actuators to project images captured by a camera onto the skin. However, this did not achieve longstanding acceptance as a viable method of assisting visually impaired people. This is given that vibratory image resolution easily overloaded users. Success was still found in determining the size, shape, and orientation of singular visual objects through simple scan, sweep, and rhythmic haptics (Rantala, 2014).

The Haptic Radar is a wearable device producing similar vibro-tactile feedback on skin. It proved effective in detecting an unseen object approaching from behind without any previous training (Cassinelli et al., 2006). However, this proof-of-concept testing involved blindfolded participants without visual impairments in a controlled laboratory setting. The system's usability for visually impaired users is therefore uncertain, particularly in more complicated obstacle preview and wayfinding tasks.

Problematically, it appears that the resolution capable by human touch sensitivity limits the volume and transfer rate of spatial and temporal visual information. The usefulness of projecting high resolution images through vibro-tactile feedback is therefore questioned, particularly as only simple object detection has been demonstrated. This is a task similarly achieved through traditional ETAs.

Notwithstanding haptic limitations, several sensory substitution systems proceeded with a focus on haptic feedback. Particularly, electro-tactile applications including the Forehead

Retina System and HamsaTouch that used surface currents for sensory triggers on the forehead and palm, respectively (Kajimoto et al., 2006; Kajimoto et al., 2014). This differentiated their approach from vibro-tactile solutions. However, these appeared to be primarily academic proofs-of-concept with limited functional performance testing. The user interface remains uncertain in its usefulness. For example, HamsaTouch required the user to position the smartphone for feature detection, which may prove difficult in users with insufficient residual vision.

BrainPort is an example of sensory substitution using electro-tactile delivery. Here, image data is captured through a head mounted camera and converted into different nerve areas of the tongue (Wicab, 2022). The device has received several iterations in the form of the BrainPort V100, BrainPort Vision Pro, and BrainPort Balance Plus. The BrainPort V100 is explored in detail considering the similar principal functionality across all devices. This iteration has also undergone multiple functional performance testing (Stronks, 2016).

Stronks (2016) finds that light perception and localisation, line orientation, and identification of simple objects were significantly increased in BrainPort users. Such increases in psychophysical ability have not been attained through traditional ETAs and EOAs, explained by sensory substitution's greater relevance to improving function over functional performance. However, this is not without its limitations: the BrainPort was not conclusively shown to improve temporal resolution and motion detection to levels above the psychophysical threshold. This is especially so in its spatial resolution, thus conferring with findings from Rantala (2014).

Further testing with subjects possessing no residual vision through cerebral visual impairment is necessary. This is given the strong cognitive demand and increased rehabilitation required to adapt the user to BrainPort's unusual interface (Nau et al., 2015). Finally, these studies were not consistent in their reporting of testing environment and user ability to interact with BrainPort. Cross-study comparability is therefore limited, hindering conclusions on sensory substitution for daily activity (Stronks, 2016).

The vOICe system by Meijer (1992) represents sensory substitution through auditory display. Audio demonstrates a successful and widely endorsed purveyance of simple spatial and temporal information (Loomis et al., 1998; Loomis et al., 2001; Meyer & Filliat, 2003; Walker et al., 2013). However, the density and rate of information delivery for sensory substitution is far beyond that of typical navigation applications. Indeed, the vOICe illustrates this by scanning visual images from left to right, converting into grayscale, and then separating each pixel according to luminance, horizontal, and vertical information.

Stereo tones of varying amplitude and frequency are then associated to each pixel; pixels on the left are played first while pixels at the top present the highest frequency. The brighter the pixel, the greater the tonal amplitude. A demonstration of the system is available online with the capacity to function on smartphones and wearables (Meijer, 2022). Auvray et al. (2007) explored the vOICe's potential benefits and limitations in early functional performance testing with six sighted participants wearing occluding goggles. It found them able to localise, point to, and recognise different objects.

While this result was promising, several experimental decisions may hinder its realistic applicability. Foremost is that the experiments were conducted in a uniformly lit white room

with dark objects intended for maximal contrast. This is compounded by the use of sighted and younger-aged participants (23 to 32 years) that may not reflect hearing deficiencies associated with the older visually impaired population (Vos et al., 2017). Brown et al. (2011) similarly utilised blindfolded sighted participants equipped with the vOICe. This assessed the capacity to identify and locate objects placed on a table by handheld or head-mounted webcam, where the former was preferred for identifying objects and the latter for locating objects. This suggests that device positioning plays a role in performance. Brown et al. (2011) extends this to the alignment of objects, where difficulty in distinguishing between simultaneous tonal pitches was observed in scenarios involving multiple vertically aligned objects. Difficulty was also found in differentiating horizontally aligned objects given the varied junctures at which tones were sounded.

In summary, the vOICe appears to present the highest spatial resolution in comparison to the priorly reviewed haptic sensory substitution systems. This is aided by its application of auditory feedback. While its functional performance testing follows similar limitations to that of other relevant systems, collective results demonstrate an effectiveness that is likely beyond chance. Haigh et al. (2013) demonstrated improved visual acuity in blindfolded sighted participants with little training, Ward and Meijer (2010) conducted visually impaired user interviews revealing an acquired auditory memory or synaesthesia-like effect, with some discerning visual depth. Proulx et al. (2014) hypothesise that such sensory substitution could benefit from and advance perceptual learning research through conjoining behavioural and neural models for multisensory perceptual learning.

Jicol et al. (2020) conducted two experiments featuring both the vOICe and BrainPort. Sighted and visually impaired participants were involved in aerial mapping tasks followed by navigation (with and without self-motion) in a three-dimensional environment. Interestingly, no learning effect for the vOICe occurred, as was observed for the BrainPort, in mapping exercises. This remains consistent with prior findings on user adaptability towards auditory feedback. Furthermore, the vOICe presented improvement in the combined use of both devices. Negligible performance difference was found relative to the singular cases, and this was attributed to high task difficulty. Multi-sensory benefit may still exist if given further time, practice, and experimentation. This was found to be true of only the visually impaired group as the number of trials increased.

The study by Jicol et al. (2020) reflects a milestone in the testing of sensory substitution systems given the controlled testing of two differing interfaces (auditory and electro-tactile) with visually impaired participants in navigation tasks. A primary conclusion moving forward is that, while both sensory substitution methods may present useable information independently, their combination does not necessitate maximal performance. This differs to traditional ETAs and EOAs where complimentary devices and use-cases are prevalent. This is especially the case given the differing forms of haptic feedback from each system, and users' subsequent perceptions towards their reliability. When combined, the device with the higher perceived reliability likely overshadows its counterpart instead of supporting it.

Ultimately, Jicol et al.'s (2020) novel experimental methodology corroborates that multi-sensory substitution should practically benefit visually impaired mobility. This is through forming rich cognitive maps and then navigating an environment. However, a paucity of information exists on the spatial and temporal capacity of these systems in realistic navigation

tasks with representative visually impaired groups. Future work on information delivery and interaction should therefore consider the novel mechanisms on which multi-sensory substitutions operate.

A prevailing theme in the preceding review of sensory substitution is that these systems aim to convey entire scenes through haptics and auditory feedback. However, a focus on feature-by-feature extraction from images has also recently developed. This includes optical recognition and auditory translation of signage (Foong et al., 2011; Wang & Tian, 2012; Dunai et al., 2018). This may appear a simpler task given a reduced information-set that must be conveyed. However, the corresponding binarization and selection processes introduce novel challenges. Three studies have been reviewed to demonstrate the different techniques used for such applications.

Based on a review of previous signage recognition systems, Foong et al. (2011) proposed a two-staged framework for digitally capturing and converting signage into an accessible format for visually impaired users. This begins with the Optical Character Recognition (OCR) of signage, followed by the integration of voice synthesis to announce the text or numerical values on the captured signage. The framework presented by the study can be practically implemented given that a JPEG image and simple computational processing is required. However, the process implanted by this study serves to highlight the shortcomings associated with optical-based systems in consideration of visually impaired mobility. The framework employed by Foong et al. (2011) has been outlined as follows.

The JPEG-format image captured must first be segmented into binary components, and this begins via conversion to grayscale, followed by the application of Otsu's thresholding method to distinguish the background and foreground per each pixel of the image (Otsu, 1975). Otsu's method yields good reliability when the signage scanned presents a bimodal distribution with clear valleys and peaks between foreground and background (Kittler & Illingworth, 1985). However, when the foreground, text, or diagram to be recognised is small relative to the background, this method can present poor results and fail to distinguish the required element correctly. Such also occurs when the lighting or contrast presented between the foreground and background is poor. These are demonstrated in the trial by Foong et al. (2011) and Kittler and Illingworth (1985).

Foong et al. (2011) instructed five blindfolded participants to capture 10 pictures of signage each using a mobile phone camera. 43 out of the 50 pictures taken returned the correct conversion of the signage. While this demonstrates a satisfactory success rate of 86%, it is unclear how the participants were able to locate (and then position) the signage to be captured. The realistic application of this study is therefore hindered.

Additionally, failure to return the correct signage conversion occurred when the sign captured was too small, or from poor lighting and contrast. This resulted from the use of the mobile phone's camera flash in this study. It is understood that signage is seldom consistent in text size, use of symbols, and colour contrast. The variability of signage and illumination therefore draws uncertainty in the effectiveness of this tool across different environments.

Furthermore, feature extraction from the processed image is typically an iterative process that requires a template of known signage and elements to allow for feature matching. Foong et al. (2011) extracted features by converting the image file to a matrix and comparing this to

template matrices of predefined characters. This is limited in that pictorial detection and irregular signage may fail to be recognised.

Other studies have attempted to alleviate the fundamental shortcomings of image processing and feature extraction. Wang and Tian (2012) developed a system capable of detecting restroom signage by first processing the image via shape detection and then using Scale-Invariant Feature Transform (SIFT) descriptors. This yielded success rates of 89.2% in detection and 84.3% in recognition. This system was superseded by Dunai et al. (2018) where machine learning was utilised through the application of Gentle Adaboost, detection via a modified Viola-Jones object recognition algorithm, and recognition through Speeded Up Robust Features (SURF) and Binary Robust Invariant Scalable Keypoints (BRISK) algorithms. Here, success rates of 84.0% in detection and 97.5% in recognition were observed. Additionally, Dunai et al. (2018) proposed this system to be implemented in a set of glasses that is worn by the user, providing a more natural experience and higher likelihood of signage detection.

These studies have demonstrated steady advancements in the technology facilitating OCR for signage, although practical testing remains limited. Table 6.8 summarises a non-exhaustive review of OCR systems to assist visually impaired people. It appears that none have practically implemented this system in real-world mobility testing. Improvements in future testing are therefore necessary to demonstrate operational effectiveness, especially in mission-critical applications.

Citation	Summary	Testing
Ezaki et al. (2004)	Tests four different character extraction methods, finding the most effective to be (in this sequence): Sobel edge detection, Otsu binarization, connected component extraction and rule-based connected component filtering.	Compared effectiveness of each method on the ICDAR 2003 Robust Reading Competition data.
Foong et al. (2011)	Proposes an OCR system based on Otsu's method followed by image matricization and comparison to a known matrix database.	Testing on 50 pictures of signage taken by five blindfolded participants.
Wang & Tian (2012)	Proposes a system where an image is first processed via shape detection and then by using Scale-Invariant Feature Transform (SIFT) descriptors.	Collected and tested database of 96 images of restroom signage.
Dunai et al. (2018)	Proposes a system which begins with the application of Gentle Adaboost, detection via a modified Viola-Jones object recognition algorithm, and recognition through SURF and BRISK algorithms.	Tested 15 images with 'Exit' signage combined with a database of 'negative' images from the internet. A total of 2000 images tested.

Table 6.8: Summary of optical object and character recognition systems for visually impaired people.

To investigate the validity of these findings in the wider application of image recognition, a novel study by Budrionis et al. (2022) is reviewed. This conducted an exhaustive systematic review of smartphone-based computer vision solutions for visually impaired people. 15 publications were reviewed, selected from 418 unique publications according to the PRISMA systematic review protocol. The reviewed publications presented prototypes, but it was also found that experimental research using commercially available solutions was not available.

This suggests that academic research into computer vision has not yielded a complete product available to visually impaired consumers.

Problematically, there appears a gap between requirements and research as the studies reviewed did not address all layers of knowledge dictating effective mobility. 8 of 15 studies addressed object recognition and scene description while the remainder investigated the user's current location and keeping them on track. However, none addressed the creation of new routes and provision of information on distant landmarks. In addition, the image processing algorithms used in all studies were described as 'not sufficiently efficient and lack robustness in real-world conditions, which is essential in this particular use case' (Budrionis et al., 2022). These included SURF and SIFT, as observed in the review of OCR systems.

Deep Learning and Neural Networks (DNNs) have the potential to reach an accuracy equivalent to that of human performance. However, the training datasets required would need to be substantial and include the classes of objects important to visually impaired mobility. This particular dataset has yet to exist. Budrionis et al. (2022) therefore suggests that a focus of future research should be the construction and publication of such a dataset, particularly considering classifications relevant to visually impaired mobility. This would also aid the evaluation and benchmarking of computer vision solutions where current research presents significant limitation by utilising their own small and unique datasets (Ezaki et al., 2004; Foong et al., 2011; Wang & Tian, 2012; Dunai et al., 2018; Budrionis et al., 2022).

Finally, all studies observed by Budrionis et al. (2022) consistently developed simple audio-based user interaction without exploration of other interaction methods and device positioning, including haptics. Further limiting the usefulness of the output prototypes is that 9 of 15 studies did not employ any user testing with visually impaired participants. For those that did, participant samples were small (typically <5) and unrepresentative of several visual impairments and age groups.

In summary, research into emerging technology including sensory substitution and computer vision has shown viability in improving visually impaired people's awareness of their surroundings. However, there remains limitations in the testing and validation of these technologies, including the high cognitive capacity, precise device positioning, and extensive datasets required for effective use. This is especially the case for wider computer vision research that consistently presents gaps between system functionality and established user requirements. Ineffective image processing techniques or unavailability of user evaluation are primary shortcomings. Commercially available computer vision solutions including eSight and OrCam are explored in section 6.3.5. This investigates the extent to which research findings, shortcomings, and mitigations have translated to devices available to end-users (eSight, 2022; OrCam, 2022).

6.3.5. Discussion on Currently Available ETAs, EOAs, and the Wayfindr Standard

6.3.5.1. Currently Available ETAs

Research continues to refine and improve traditional ETA and EOA functionality, both in system design and their underpinning technology. This has led to the widespread availability of ETAs and EOAs that was previously unrealised by historic devices. These often leverage previously unavailable solutions including global positioning, image recognition, artificial

intelligence, and smaller and more powerful computing components (Roentgen et al., 2011; Real and Araujo, 2019; Feghali et al., 2021; OrCam, 2022).

ETAs have been implemented in new wearable form factors as a benefit of the decreasing size and cost of sensors and microprocessors, described in Figure 6.6 (Real & Araujo, 2019). Head-mounted devices (A) allow for easier, more natural tracking of objects within the user's line of sight, hence being preferred for camera or artificial vision-based approaches. Wrist (B) and cane-mounted (C) devices allow for wider scanning movements and typically provide traditional ETA functionality in haptic obstacle detection. BEMS have recently taken this form in the WeWALK smart cane (Feghali et al., 2021). In conjunction to placement, the portability, usability, and field of view of these devices are important considerations. Available examples of each are therefore explored to determine user requirements (Real and Araujo, 2019; Jeganathan et al., 2019).



Figure 6.6: Positioning of wearable ETAs (Real & Araujo, 2019).

Epson smart glasses, NuEyes, and eSight are the currently available examples of head-mounted devices (A) where a glasses-mounted camera projects a moving image of the user's surroundings through a screen. This stimulates synaptic activity from the remaining photoreceptor function of the eyes (Epson, 2022; NuEyes, 2022; eSight, 2022). This novel application is in a similar category to glasses and other corrective devices, bringing it the closest to directly influencing the user's visual function than other assistive technology (outside of medical intervention at the organ-level).

In this regard, improvements in visual function were noted by Lorenzini et al. (2017) in 13 participants, aged 36 to 63, with hereditary visual diseases and low vision (visual acuity of 20/63 to 20/400 in the better eye) using eSight. These were in near and distance visual acuity, contrast sensitivity, and reading speed in all participants. Further improvements in distance visual acuity proceeded with three months of practice. This study was limited in sample size and testing duration, thus limiting conclusions on real-world mobility performance. Although, such consistent findings across all participants should predict some improvement in this context.

A study by Jeganathan et al. (2019) found similar visual function improvement across participants using all three aforementioned head-mounted devices, albeit self-reported.

However, it was stated that 'though the majority of participants noted they had difficulty in certain mobility scenarios, zero participants could imagine using current [head-mounted devices] to walk or navigate' (Jeganathan et al., 2019). The short-term nature of this study similarly limits conclusions on how this result may change through practice and long-term observation.

The results from Jeganathan et al. (2019) are further investigated as they present novel insight into user requirements from a combination of head-mounted displays. This is especially as the participant sample was moderately sized at 18 people (aged 30 to 83) with a range of visual impairments. These included varying losses in central and peripheral vision (with visual acuity ranging from 20/150 to 20/20).

Usability was the largest influence on participant preference, particularly in the positioning, speed, and ease-of-use of the device's controls. The eSight received praise here, especially from participants with the lowest self-reported well-being. The actual performance of the device was also a primary determinant of preference, particularly for those with higher reported well-being in the context of clarity, magnification, and wireless operability.

These participants also expressed an interest in the device's appearance, noting the NuEyes as 'being more comfortable and looking more normal'. Notwithstanding this, comfort, appearance, and specific improvements in visual function appeared to be of the least priority (Figure 6.7). These findings should therefore be considered in the design of future head-mounted displays of this class.

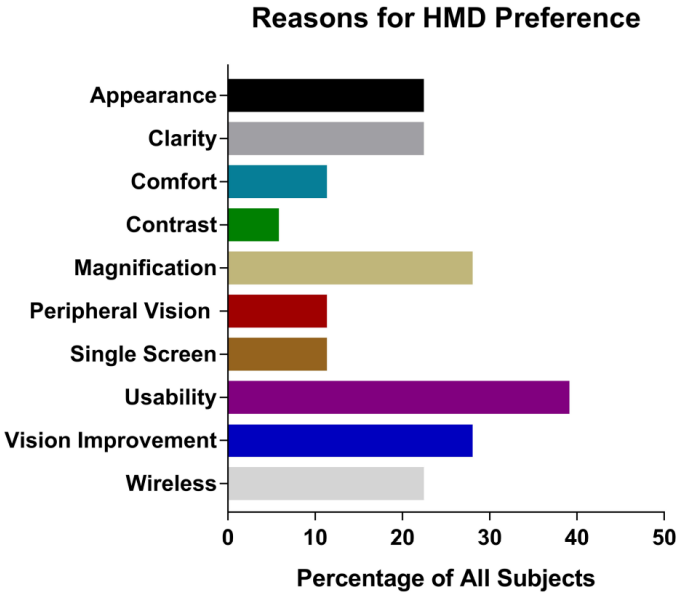


Figure 6.7: Preferences of HMD users surveyed by Jeganathan et al. (2019).

The other currently available solution, OrCam, primarily targets text and object recognition rather than wayfinding, positioning, and other mobility-related tasks (OrCam, 2022). To this effect, Waisbourd et al. (2019) concluded that OrCam enabled blind participants to improve their quality of life through being able to read independently when in controlled settings. The device was not suitable for street signs and other similar mobility applications when the location of text was not apparent. Such findings correlate with those from the investigation of experimental image recognition and sensory-substituting head-mounted devices. Particularly,

the usability challenge of locating the required object for system interpretation prevails in head-mounted devices.

The Sunu Band is the currently available example of the wrist-mounted device. It performs similarly to a BEMS in that it detects obstacles through ultrasonic sensing and haptic feedback, while also connecting to the Sunu smartphone application (Sunu, 2022). The device has been recognised in literature summarising available visually impaired mobility aids including Real and Araujo (2019) and Gupta et al. (2021). Although, no functional performance testing with users was found. Such is also the case for Maptic, a similar wrist and smartphone-based solution with the addition of a LIDAR sensor worn by the user as a necklace (Farrington-Arnas, 2022).

Cane-based devices have become well-established given early implementations such as the GuideCane. Research and product development iteratively adds new functionality to this class of device. The UltraCane is a device that replaces a white cane's grip with a new handle comprising two ultrasonic sensors and two corresponding tactile buttons for head and chest-level obstacle detection (UltraCane, 2022). Roentgen et al. (2012) examined the UltaCane and MiniGuide's impact on eight severely visually impaired participants' PPWS, type and number of mobility incidents, and self-reported functionality and satisfaction. No ophthalmologic assessment was conducted. The MiniGuide is a small handheld device using ultrasonic sensing and user-selectable haptic or audio feedback for obstacle detection (Pamtrad, 2022).

Roentgen et al. (2012) found a significant mean walking speed decrease of 21% (2 s.f.) with the use of the UltraCane versus a regular cane, and a non-significant decrease with the MiniGuide. Mobility incidents significantly decreased with both devices (45% and 54% decreases with the UltraCane and MiniGuide, respectively). Correspondingly. user satisfaction was favourable to both devices, with similar ranking in self-reported safety, effectiveness, ease-of-use, and ability to adjust device settings.

Weight was noted as a key differentiator in user opinion, with several favouring the MiniGuide for its portability and far smaller grip requirements versus that of the UltraCane. Contrastingly, the significant difference in sensing distance and granularity between the two devices were not noted as being significant in user performance (two modes from two to four meters in the UltraCane and 13 modes from half a meter to 8 meters in the MiniGuide). Users found the UltraCane's implementation sufficient. Ease-of-use therefore appears to preside over information range and granularity in the context of these device-classes.

Roentgen et al. (2012) is novel as it addressed the scarcity of available research on the effectiveness of at-market mobility aids. It also compared two devices with different form-factors. Moreover, while the sample size was small and tested only independent travellers indoors, a representative age range of 26 to 70 years with a mean of 50.13 was used. This is further strengthened by including both congenital and age-related impairments, and a one-day pre-experiment training session with participants (albeit limited in time). Mobility testing also considered recommendations from Soong et al. (2001) and Leat and Lovie-Kitchin (2006) in PWS measurement and mobility course construction, respectively.

Roentgen et al. (2012) attributed reduced walking speeds to limited practice. Similar conclusions were drawn by Penrod et al. (2007) and McKinley et al. (1994) in pilot evaluations of the UltraCane and Sonic Pathfinder, respectively. This suggests that, regardless of

formfactor, walking speed may not be indicative of user satisfaction or effectiveness of an ETA. The necessity of self-reported outcome measures in the testing of such devices is therefore corroborated, particularly considering the user requirement of reduced size and weight.

Improvements in mobility technology and their adoption in research is an iterative process. This is exemplified by the Augmented Cane from Slade et al. (2021) that mimics the GuideCane's functionality, albeit with added computer vision sensing and GPS routing to enhance the cane-steering functionality. The Augmented Cane is not currently available to users, although findings from Roentgen et al. (2012) raise concerns as to its significantly increased weight (of an additional 1 kg) and visibly larger size versus a traditional white cane. From left to right, Figure 6.8 illustrates this by displaying a standard white cane (United States. Department of Veterans Affairs, 2016), the UltraCane (UltraCane, 2022), and the Augmented Cane (Slade et al., 2021).

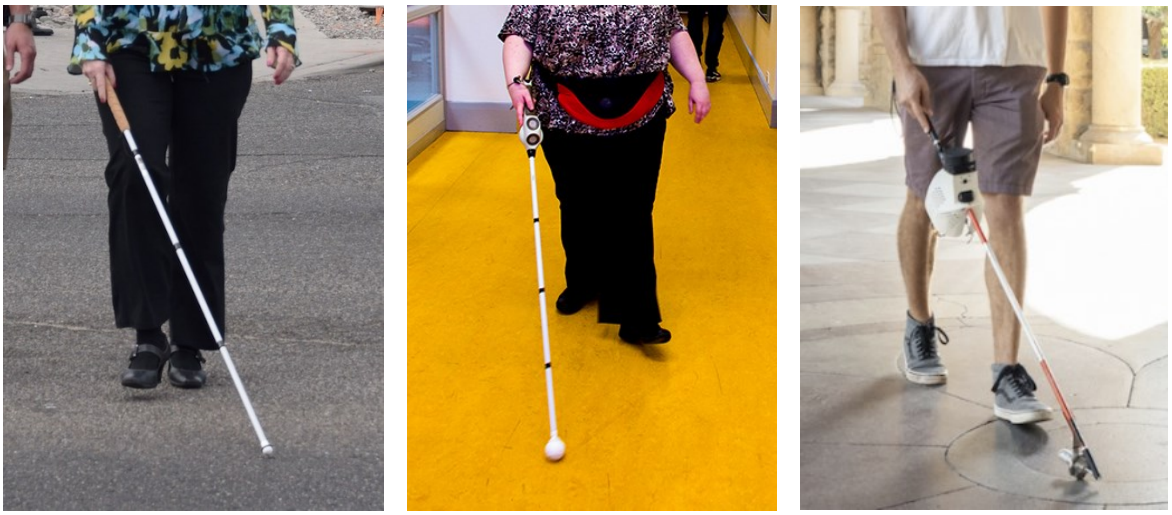


Figure 6.8: From left to right, a standard white cane (United States. Department of Veterans Affairs, 2016), the UltraCane (UltraCane, 2022), and the Augmented Cane (Slade et al., 2021).

Further academic research to support the Augmented Cane could not be found. However, Tjandra (2021) does quote two independent visually impaired people as presenting similar usability concerns towards this device, particularly in that the 'design may be based on a misconception about cane travel' as the tactile audible feedback from a standard cane hitting an object is its primary purpose (Shah, 2021).

Notwithstanding these limitations, improvements in walking speed were shown in 24 participants in an indoor obstacle avoidance course and outdoor GPS-based routing course with stop-sign identification. Notably, all participants were blindfolded with half having a visual impairment (the 'expert' group) and half acting as a control with no visual impairment (the 'novice' group). While blindfolding has been discussed as an unideal experimental method in realistic functional performance testing, the consistency in walking speed and self-reported improvement suggests a useful device. This also contrasts findings from other ETAs (Roentgen et al., 2012; Penrod et al., 2007). This is especially as benefit was also found in the novice group. Here, poorer tacit knowledge and cognitive mapping capability would have limited mobility.

Slade et al. (2021) attribute this to accurate steering assistance, reduced cognitive load, fewer contacts with the environment, and confidence in the device. These are noted as important user requirements for cane-base devices. The behaviour of such a device with dynamic obstacles including crowds should be explored in future work, given the impacts of subtle turning movements on crowd performance (Chapter 5).

Finally, the WeWALK smart cane is a novel cane-based device with a similar form-factor to the UltraCane in that it replaces the standard white cane's handle (WeWALK, 2022). The device combines a single ultrasonic sensor and haptic feedback for obstacle detection, as well as a touchpad, speaker, microphone, Inertial Measurement Unit (IMU) sensor, microprocessor, and Bluetooth module to facilitate smartphone connectivity. In conjunction with the WeWALK companion smartphone application, the device combines its compass heading data with positioning from the smartphone's inbuilt GPS readings. This facilitates positioning according to the cane's heading.

Such alleviates the need for the connected smartphone to be held in a forward-facing orientation during navigation. It also allows for user input from the cane through touchpad and audio interaction. When paired, the device provides primary ETA functionality through obstacle detection, and EOA functionality through walking and public transport navigation with audio guidance (Feghali et al., 2021). This combination constitutes WeWALK's designation as a BEMS, while also allowing for Over-The-Air (OTA) expandability through software and firmware updates.

An example of this feature expansion is the novel use of these built-in sensors for users' long-term functional performance measurement. Metrics measured include average walking speed, time spent mobilising, places visited, cane swipe count, and cane swipe width (Feghali et al., 2021; Microsoft, 2021; Lanxon, 2021). Controlled user testing has not been conducted to demonstrate the system's effectiveness, especially in discretising the individual and combined impact of WeWALK's ETA and EOA functionality.

6.3.5.2. Currently Available EOAs

In conjunction with ETAs, several EOAs have prevailed, particularly those with GPS functionality. Early standalone devices included the BrailleNote and Trekker Breeze, handheld devices inputting map information through SD cards and outputting the user's position and nearby landmarks from a database. In parallel, other devices built on smartphone platforms including the Trekker and Wayfinder Access were incepted (Roentgen et al., 2011; Real & Araujo, 2019).

Roentgen et al. (2011) examined the performance of these devices through practical mobility testing and semi-structured interviews with 18 severely visually impaired participants (where details on visual impairment were self-reported). While an exploratory and qualitative approach was undertaken by this study, the shortcomings and benefits of these devices and their underpinning technology became apparent. This was in the two distinct groups that formed during testing. One group found the devices useful in unfamiliar routes, and another did not. This was because of limited accuracy in positioning, insufficient information on crossings and other landmarks, or a combination of both. Notably, the former group also presented higher O&M proficiency and reported being more independent than the latter. It is

therefore suggested that these devices supplement independent mobility, rather than facilitating it. Roentgen et al. (2011) represents a short-term study, however, and the use of these devices for long term O&M development has yet to be understood.

Rising smartphone availability and performance of mobile networks has led to several accessibility enhancements in smartphone interface design, including screen-readers (such as VoiceOver and TalkBack) and voice assistants (such as Siri and Google Assistant) (Akkara & Kuriakose, 2019). Subsequently, the provision of navigation has shifted from standalone devices to visually impaired-specific smartphone applications. Namely, Nearby Explorer, BlindSquare, Ariadne GPS, Seeing Eye GPS, FAR Vision, Lazarillo, Eye-D Pro, GetThere GPS, Soundscape, and RightHear (Feghali et al., 2021; Akkara & Kuriakose, 2019; Microsoft, 2022). These applications attempt to deliver information on nearby Points of Interests (POIs) and walking navigation with destination tracking to varying degrees of customisation. For instance, Soundscape uses spatial audio beacons, BlindSquare delivers a text-based interface, and Lazarillo includes high-contrast mapping for users with residual vision. However, Real and Araujo (2019) note:

> 'a major flaw in the design of navigation systems for [blind and visually impaired] users seems to lie in a set of reiterated deficiencies concerning the knowledge of the users' needs, capabilities, limitations, etc., despite the great amount of work that has accumulated over the last few decades.'

Indeed, this sentiment extends to these solutions as none wholly deliver on the set of requirements from Strothotte et al. (1996), Bradley and Dunlop (2004), and Lewis et al. (2015). This is especially the case concerning the provision of knowledge on public transport, the importance of which was made apparent by Sanchez and Maureira (2007). The listed visually impaired-specific solutions do not include the multi-modal navigation functionality currently available in industry-wide navigation applications including Google Maps, Apple Maps, Moovit, and CityMapper. These use visually driven interfaces without a focus on visual impairment (Google, 2022; Apple, 2022; Moovit, 2022; Citymapper, 2022; Feghali et al., 2021; Akkara & Kuriakose, 2019). It is deduced that the visually impaired user would have to compromise on information availability or interface accessibility when deciding on which navigation application to use.

As explored by Real and Araujo (2019), outdoor mapping and transport Application Programming Interfaces (APIs) have become available for third-party navigation applications to employ. These include APIs from Google and Moovit (Google, 2022; Moovit, 2021). Such is why Feghali et al. (2021) prioritises transport integration and multi-modal navigation in the design of the WeWALK smartphone application, partnering with Moovit. Through access to the Moovit API, transport functionality is implemented with interface considerations for visually impaired users (Moovit, 2021; Forbes, 2021; TechCrunch, 2021). A description of WeWALK's navigation functionality is included in Chapter 7 to exemplify the practical implementation of the requirements derived throughout this thesis.

Availability beyond outdoor environments has been a focal point in research, especially given well-established outdoor navigation systems that cannot effectively function in indoor environments (Real & Araujo, 2019; Simões et al., 2020). However, there exists a broader set of requirements and challenges that indoor-capable systems must consider, summarised as follows (Simões et al., 2020; Real & Araujo, 2019; Elhajj & Feghali, 2020; Wayfindr, 2018):

1. The system must provide reliable and accurate position estimates, preferably with integrity monitoring to diagnose failures in this context and alert the user.
2. The system must be easily scalable in various indoor environments, especially considering the high system-availability requirements observed by Lewis et al. (2015).
3. The system must be cost-effective in setup, operation, and maintenance.
4. The system must consider the user's accessibility and usability requirements, delivering appropriate information classification and interaction methods.

Indoor positioning solutions have remained largely unavailable, especially for visually impaired wayfinding applications. To this effect, Simões et al. (2020) conducted a literature review on indoor positioning techniques and technology for visually impaired people. A key output of which is a review of positioning technologies, their precision, and weaknesses, as reproduced in Table 6.9.

Technology	Precision	Weaknesses
TDoA [1]	1.34–1.50 m	Infrastructure
RSSI [2]	1.80–6.00 m	Low precision, access point
RSSI [2]/ SNR [3]	2.40 m	Infrastructure
RFID [4]	0.32 m	Very low precision
ZigBee	0.25 m	Special equipment
Audio	1.30 m	Sensitive to audio noise
Ultrasonic	1.00 m	Infrastructure
Ultrasonic with TDoA [1]	0.35 m	Infrastructure
VLC [5]	0.20–0.23 m	Infrastructure
Fixed camera	0.10 m	Sensitive to light conditions
Mobile camera	0.20 m	Sensitive to light conditions
VLC [5]/Wi-Fi [6]/inertial sensor	0.23 m	Infrastructure
Inertial	0.30–2.50 m	Sensitive to the presence of metallic materials and people
Inertial with camera	0.50 m	Sensitive to light conditions
Wi-Fi with inertial	1.35–4.00 m	Sensitive to the presence of metallic materials, people, and blocking signals by the infrastructure
Wi-Fi [6] with camera	0.20 m	Sensitive to light conditions
Infrared with camera	0.70 m	Sunlight, sensitive to light conditions

[1] TDoA—Time Difference of Arrival [2] RSSI—Received Signal Strength Indication [3] SNR—Signal-to-Noise Ratio [4] RFID—Radio-Frequency Identification [5] VLC—Visible Light Communication [6] Wi-Fi—Wireless Fidelity.

Table 6.9: Summary of indoor positioning technology (Simões et al., 2020).

In comparison to GPS in outdoor use, it appears that all indoor positioning technologies (except for RSSI's upper bound) may surpass the accuracy of GPS-enabled smartphones. Smartphones are typically accurate to within a 4.9 m radius under open sky with significantly worsened reliability and availability under cover from buildings, trees, bridges, and other such structures (van Diggelen & Enge, 2015). Dual-frequency receivers and other high-end components can improve GPS accuracy to millimetre level in long-term measurement. However, the positioning accuracy available in consumer equipment has allowed Trekker, BrailleNote GPS, BlindSquare, and other related products to become available, suggesting sufficient usability for outdoor navigation (Real & Araujo. 2019).

It can therefore be inferred that accuracy is not the only limiting factor in the uptake of indoor positioning. Simões et al. (2020) introduces issues of cost, maintenance, and infrastructure dependencies. Firstly, the most accurate positioning technologies require certain infrastructure specific to that technology; for instance, VLC-based positioning would require the installation

of LED transmitters (or another specific light-emitting device), and this would not support a Wi-Fi or Bluetooth-based system. Moreover, positioning techniques including TDOA, while applicable in principle to both examples, would not be easily transferrable between them. This is given the high sensitivity of system accuracy to specific environments and hardware configurations. For instance, Faragher and Harle (2015) and Luo et al. (2017) applied triangulation to Bluetooth and VLC-based positioning, yet obtained accuracies of 2.08 m and 0.10 m, respectively.

In turn, issues in component selection and availability arise. This remains the case in devices that are seemingly widespread such as smartphones. Smartphones now incorporate sensors capable of delivering the Wi-Fi, Bluetooth, BLE, IMU, and camera-based positioning in Table 6.9. Although, a standard approach to positioning with these components has yet to exist as a result of the unique application of each positioning system across research (Simões et al., 2020). This is especially the case when considering high infrastructure demands associated with each technology.

The combinations of positioning techniques can improve accuracy and availability, as is presented in the combination of Wi-Fi and inertial or camera-based sensing. Elhajj and Feghali (2020) explore how a hybrid of Bluetooth and inertial positioning can produce complementary positioning solutions where each system accounts for the other's deficiencies. Consequently, an agreeable standard is difficult to reach given the numerous techniques and combinations that are currently being, or have yet to be, explored.

Following a selection of positioning technique, an issue of mapping and scale arises. Nagarajan et al. (2019) and Aziz et al. (2019) describe that positioning systems can be discretised into those that use maps, or those that are free-mapping (identifying paths, objects, and other environmental items within a set radius that forms the system's information-base). Limitations exist as indoor maps, unlike outdoor maps, are not readily available or standardised in format.

Moreover, maps for larger indoor spaces present cost-limitations, further exacerbated by the level of detail and update frequency required (Simões et al., 2020). The enhancement of Simultaneous Localisation and Mapping (SLAM), such as that employed by Jin et al. (2020) using visual sensing and machine learning, has therefore become prevalent in emerging indoor positioning technology. Although, this is still in its infancy without commercial application. This leads Simões et al. (2020) to conclude that:

> 'There is still no satisfactory solution to the problem of an Indoor Positioning System (IPS) capable of being used in all indoor scenarios with standard behaviour. Fully accurate solutions are costly, or they are not in real time, or cheaper proposals are very inaccurate.'

In addition to the positioning technology, the user requirements for an indoor navigation system are different than those of its outdoor counterpart (Bradley & Dunlop, 2004). Consideration must also be given to the system's integrity and whether users and system operators can maintain their trust, security, and privacy in using the system (Elhajj & Feghali, 2020; Chopra et al., 2017). Moreover, considerations of form-factor, usability, and interaction methods prevail. Such is why indoor wayfinding requirements for visually impaired people has received attention through the Wayfindr (2018) open standard.

6.3.5.3. The Wayfindr Standard

The Wayfindr (2018) open standard, published in March 2018 as Version 2.0, is a comprehensive standard for digital navigation service providers and venue owners. The aim of the standard is to overview the requirements of visually impaired individuals in indoor spaces. Guidelines are then set for navigation providers to meet them.

The standard is therefore reviewed in detail given its unique position in influencing future navigation system designs. Indeed, indoor positioning trials based on this standard have already been conducted by TfL (2015b), although deployment has yet to occur on any TfL infrastructure. To aid this process, the Wayfindr standard was reviewed with contributions from subject-matter experts at the RNIB through open discussion (Spinks et al., 2021).

The standard commences by overviewing the Orientation and Mobility (O&M) capacity of a visually impaired person, then proceeds to investigate mobile interface design. This includes audio guidance, and the environmental landmarks to which navigation systems should alert the user to. However, the standard fails to identify specific details within each section that are necessary for a complete system. For instance, the standard does not consider the cognitive load that is placed on the visually impaired person in the environments in which it describes. This is important as an excess of information would lead to reduced navigational performance (Strothotte et al., 1996; Lewis et al., 2015). The standard is therefore at risk of providing users with unnecessary information, or information that may lead to disorientation or confusion when navigating.

In agreement with Strothotte et al. (1996) and Lewis et al. (2015), the standard is reasonable in including hazard identification as an essential requirement. However, the standard fails to consider how this can be achieved according to the task the individual is carrying out, and whether this is critical or non-critical to this task. Spinks et al. (2021) exemplifies this by adding that an escalator should only be described to the user if the user will interact with it. The possibility of user preference input is not considered here. Furthermore, no distinction is made between permanent and temporary obstacles.

Spinks et al. (2021) describes a liability on navigation systems built to the standard as it suggests the provision of tactile paving information. Users' fundamental O&M training should allow them to identify this without the use of such a system. Moreover, the inconsistent application of tactile paving elevates risk. An excessive dependence on the navigation system may also prevail. The standard does not consider performance metrics to evaluate system functionality and use. These can include walking speed, cognitive load, path efficiency, self-report, and other O&M outcome measures described in Chapter 3.

Complex environments such as a train station require a user to carry out several subtasks within them. Subsequently, the user may interact with several elements within this environment. Wayfindr (2018) identifies the following which have been included in the requirements summarised in Chapter 7: Entrances and exits, pathways, decision points, tactile walking surface indicators, warning walking surface indicators, directional walking surface indicators, escalators, stairs, lifts, ticket control gates and barriers, and platforms.

In the context of a train station (or any public transport route), there exists a start and end station, each influencing the user's motivations within them. For instance, the user is likelier to require navigation to a ticket machine at the start station while, at an end station, finding an

exit would be the priority. In lieu of this, the standard assumes each environment to be a single entity within the journey. Although, the standard does suggest 'segmenting' routes without further detail. Consideration is made for environment-specific features including platforms and ticket control gates, but other indoor spaces beyond train stations are not detailed. This constitutes a literature gap as indoor navigation can operate in environments beyond train stations. Additionally, this corroborates the need to understand the challenges and motivations of visually impaired people in these environments.

Spinks et al. (2021) noted inconsistencies in the level of detail suggested by the standard for certain landmark information. Firstly, there was insufficient consideration for accessible toilets. Secondly, descriptions of the visual appearance of steps, such as the number of steps to be descended or ascended, were unfavourable and confusing. Therefore, it was suggested that an improved approach is the description of descents or ascents as being short or long. Allowing users to select their preferred approach would be the ideal solution.

Finally, it was observed that the standard does not comprehensively include user interface options. This is especially when considering the numerous advancements established through prior ETAs, EOAs, and sensory substitution devices. Particularly, the standard only discusses simple audio notifications from a mobile application that are similar to those found in Lewis et al. (2015). Feedback through spatial audio, haptics, audio icons, and other emerging technologies is not included. Indeed, the standard only assumes audio cues for navigation whereas this may not be accessible, or relevant, for all users.

In summary, there is an unavailability of indoor navigation systems for visually impaired people with widespread use. Instead, several highly localised or mission-specific attempts have surfaced, often acting as proofs-of-concept rather than complete wayfinding tools. The Wayfindr (2018) system delivered the first standard for visually impaired indoor navigation yet did not expand beyond the trials described by TfL (2015b). Other examples include British telecom operator O2 (2019) that installed iBeacons and employed the Buru Navi handheld device to guide users around a room at the O2 Arena in London. This was followed by Ultra-Wideband (UWB) positioning to locate a specific seat in the arena. No further academic or commercial validation of the system has been found.

Simões et al. (2020) concluded that academic research has produced positioning solutions with high accuracy, but often with infrastructure and implementation requirements that challenged cost-effectiveness and scalability. Other ETAs and EOAs with indoor use-cases have presented usability barriers, including the Augmented Cane (Slade, 2021), OrCam (Waisbourd et al., 2019), and eSight (Jeganathan et al., 2019). This suggests that additional development is necessary to guide a visually impaired user through an indoor space. This thesis' objective in validating a navigation system for visually impaired people is therefore corroborated.

6.4. Conclusions on the Current Methods of Augmenting the Mobility Performance of the Visually Impaired

It is evident that environmental augmentations have been developed for visually impaired people, including standards for visual, auditory, and tactile reference. However, these have not demonstrated sufficient availability and reliability to meet the needs of users in all scenarios. In the event that they fail or become unavailable, the user is left to access the environment

according to their own ability. Mobility aids for personal use have therefore been developed, and these can be broadly categorised into ETAs, EOAs, BEMS, or sensory substitution devices.

Tools such as sensory substitution devices have demonstrated improved ability to carry out specific tasks, such as detecting objects on a table. Moreover, indoor PNT techniques have improved the reliability of positioning in spaces outside of GPS availability. Visually impaired people utilise several indoor and outdoor environments, and demand accuracy and reliability. However, this demand has been primarily addressed outdoors, and not indoors, given limitations in technology, cost, and scalability.

Two primary challenges are found in the design of mobility aids. First, is the classification of information. Second, is ensuring its appropriate and accessible delivery. Classification is well understood, but information sources to provide this level of detail are sparse, segmented, and do not operate in all environments. Multisensory delivery methods have been developed and tested, and positive results have been demonstrated through the use of audio and haptic cues for navigation and obstacle avoidance. User requirements for these technologies have also been derived through several studies including Lewis et al. (2015) and Wayfindr (2018). A literature gap remains in that state-of-the-art research has yet to consolidate these requirements in considering mobility capacity (defined in chapter 3), and mobility performance.

A critical gap found throughout this literature review is in the validation processes used throughout the development of mobility aids. Studies either employed specific tasks not relevant to all environments (such as crossing streets or accessing transport signage) or utilised generic tasks that would not consider the nature of the user's environment (such as identifying objects on a table). A literature gap arises in that visually impaired people require a navigation system with indoor use, but that this has yet to be fulfilled with rigorous coverage of user requirements. This thesis therefore proposes these requirements, and contributes them to the development of such a system in Chapter 7 and 8.

Beyond physical interaction with environments, existing research could not include timeframes to capture changes in cognitive load experienced in realistic environments. Kuller (1991) explains that two stages are involved in mood changes, termed phasic and tonic arousal. The first consists of the initial reaction to the environmental setting, while the second is related to a long-term habitation with that setting. Visually impaired people are likely to endure several shifts according to their familiarity with their environment. Environmental augmentation and mobility tools should allow for this, such as the practicing of a mobility tool with users prior to mobility testing.

Finally, research could not be found to assess and compare the challenges of visually impaired people across different environments. This includes streets, shared spaces, shopping centres, gyms, and hotels. Such could greatly benefit the development of environmental augmentations and mobility tools. Particularly, it would present the critical challenges to be addressed for each environment, allowing for a targeted augmentation. Accordingly, this thesis conducts experimentation with visually impaired people to define the different challenges and coping mechanisms that could arise in these environments (Chapter 9).

7. Human, Environmental, and Technological Requirements for Visually Impaired Mobility

This chapter consolidates the findings from all prior chapters to present a condensed set of principles and requirements for visually impaired mobility. Section 7.1 describes the requirements for measuring and modelling visually impaired mobility. This incorporates mobility capacity, mobility performance, environmental and technological factors, and the use of mobility outcome measures. Section 7.2 lists the requirements for navigation systems for visually impaired people. Operating principles, system coverage, items and routes, and environmental features are included. Finally, the contribution of these requirements to the WeWALK system is explored. Practical experimentation is then conducted in Chapter 8 to validate these requirements and identify system shortcomings.

7.1. Requirements for Measuring and Modelling Visually Impaired Mobility

7.1.1. Mobility Capacity and Mobility Performance

From the literature reviews and experimentation conducted in this thesis, the process of investigating visually impaired mobility is summarised. Figure 7.1. shows the relationship between capacity and performance, and how they then feedback into behavioural modelling. Mobility capacity is the fundamental ability of the individual to mobilise. Measuring this typically requires a controlled setting, often in a laboratory where physiological and psychological elements can be optimised individually. Mobility performance is the realistic ability of an individual to mobilise accounting for their motivation, and the influence of the relevant environment and mobility tools.

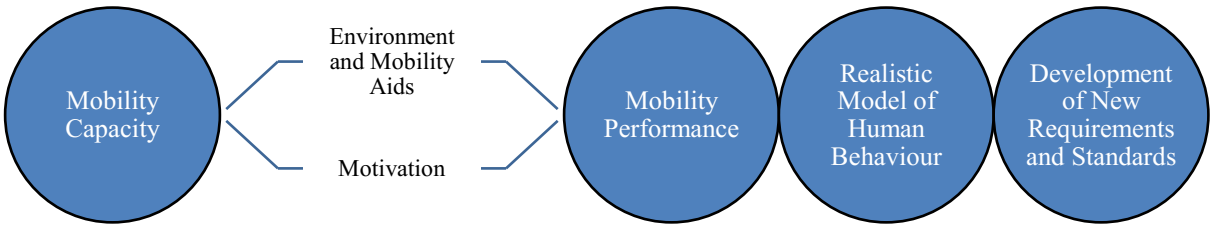


Figure 7.1: Transitioning from mobility capacity to the development of new requirements.

Separating capacity from performance is a difficult process as the composition of a controlled testing environment, regardless of how empirical, may unintentionally affect the individual. For example, while lighting may be optimised to ensure that it does not limit an individual's capacity to detect the environment, the directionality of the light source may act as an orientation aid. Therefore, an understanding of mobility capacity and performance is derived through an iterative process where an individual's motivation, environment, and mobility tools are each isolated, tested, and iterated.

As explored in Chapter 3, the current understanding of visually impaired mobility capacity is dependent on the factors listed in Figure 7.2. Operation as an individual or in a group is the fundamental consideration when modelling mobility capacity. This is as the effective

modelling of human behaviour combines a microscopic (individual-level) and macroscopic (group-level) approach into one that is mesoscopic (both individual and group-level).

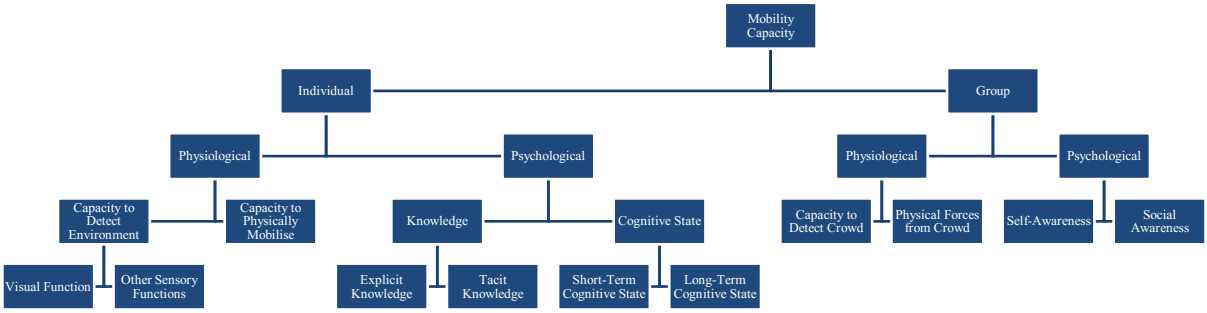


Figure 7.2: Factors that influence the mobility capacity of a VIP.

Both individual and group scenarios contain physiological and psychological factors. As an individual, the capacity to detect the environment through sensory functions is a well-researched field. This thesis describes, in detail, the mobility repercussions of diminished visual functions including visual acuity, visual field, and contrast and colour sensitivity. Moreover, a qualitative approach is adopted to identify other sensory functions comprising auditory, haptic, and olfactory response. Note that a quantitative analysis is outside the scope of this thesis given its focus on visual impairment. For the same reason, the capacity to physically mobilise is only addressed at a high level.

Physiological components include a person's explicit and tacit knowledge of the environment, and their short and long-term psychological state. Knowledge comprises of several levels incorporating the immediate and distant environment. As with sensory capacity, limitations of the ability to acquire knowledge, in turn, limit mobility. Furthermore, short-term cognitive state is a by-product of long-term cognitive state. This is, for example, the instantaneous fear, discomfort, or lack of confidence experienced by individuals undergoing mental trauma, shock, or other emotional adjustment to vision loss. This has been shown to be the primary determinant of an individual's mobility capacity given that adjustment of walking speed is a reaction to short-term cognitive state.

The experiment conducted in Chapter 5 of this thesis uncovers group factors not previously identified in the literature. Firstly, the capacity to detect a crowd allows for Visually Impaired Participants (VIPs) to couple with Normally Sighted Participants (NSPs), whether it is through visual, haptic, or auditory function. This typically improves a VIPs' psychological performance, particularly in VIPs' self-awareness (comfort in knowing there are people around to assist) and NSPs' social awareness (allowing the VIP space and assisting when needed).

This interaction between participants results in an average improvement in mobility capacity. However, it does not negate the limiting effects of physical forces from the crowd, particularly

in opposing versus unidirectional flows; these are lane formations, bottlenecks, deadlocking, interactions at intersections, and the emergence of self-organised formations. Notwithstanding these outcomes, the classical inverse relationship between speed and density is found to not be representative of group conditions involving VIPs. This is especially the case when observing differences between unrestricted and restricted flows, where a psychological instruction yields reduced walking speeds for the whole group even though the group size, composition, environment, and maximum density remain identical. Individual, unidirectional, and opposing flows (including restricted and unrestricted conditions) should each be considered in models. This is given the significant variations in group behaviour among them.

In developing mobility performance, as is concurrent in several studies (Strothotte et al., 1996; Loomis et al., 2001; Feghali et al., 2021), the overarching requirements of a visually impaired individual are:

1. Obstacle and hazard awareness
2. Orientation and wayfinding ('Where am I?')

A pedestrian conducts 'active planning' where internal decisions may be influenced by external decisions. These are irrespective of functional or recreational mobility (Davies et al., 2012). Operational scenarios involve a sequence of changing motivations, comprising of tasks (macroscopic phases) and subtasks (microscopic phases) where the pedestrian:

1. Acquires information (recognises the visual, auditory, olfactory, or tactile reference point)
2. Orientates (processes the acquired information)
3. Navigates (reacts to the acquired information)
4. Transitions between each task and subtask within their environment (Foltz, 1998).

Environmental augmentations and mobility aids are the prominent intervention methods to enhance mobility performance. The following are environmental augmentations that have been demonstrated to improve mobility performance when optimised:

1. Illuminance level and colour temperature
2. Contrast and colour
3. Signage
4. Auditory, olfactory, and tactile interaction

Increasing illuminance broadly improves mobility performance, particularly for visually impaired people with reduced contrast sensitivity and dim-light vision. However, illuminance above an environmentally-dependant threshold may induce disability glare. Research on colour temperature indicates better alertness at cooler colour temperatures, although this has not been verified on a visually impaired test group. Contrast conjoins with illuminance in that both should be maximised concurrently, where poor illuminance and good contrast between surfaces (and vice versa) are unideal for visibility and performance.

National standards (BS 8300 and TfL's station design idioms) propose illuminances of between 150-300 lx depending on application, and contrast is determined according to Light Reflectance Value (LRV) where values exceeding 30 are acceptable. These are shown to be simplistic, and a research gap is observed in which hue and chroma are not considered within these standards, although their ramifications on environmental visibility is demonstrated. Future work should

specify appropriate standards for colour temperature, hue, chroma, and their implications on perceived contrast and measured mobility performance.

In conjunction with environmental augmentations, mobility tools have been created to assist visually impaired people. Feghali et al. (2021) summarises the three different categories of mobility aid that exist:

1. Electronic Travel Aids (ETAs) for obstacle detection and hazard awareness
2. Electronic Orientation Aids (EOAs) for orientation and wayfinding ('Where am I?')
3. Binary Electronic Mobility Systems (BEMS) that attempt to combine the benefits of both ETAs and EOAs.

To be effective, these tools must consider two primary challenges:

1. Classifying information that is useful to the user.
2. Delivering this information to the user in an accessible and useable format.

Early devices were predominantly ETAs that could not overcome these challenges; they only addressed the obstacle detection requirements of visually impaired users, and not their orientation and navigation needs. The invention of EOAs aimed to rectify this. However, the underlying positioning technology employed by current EOAs is unable to provide indoor and outdoor coverage. Therefore, users are confined to several ETAs and EOAs according to the scenario in which they must operate.

BEMS, characterised by the novel WeWALK smart cane, rectify the need to carry both an ETA and EOA by combining their functionalities into a single device (Feghali et al., 2021). The limitations of the underlying positioning technology prevail, although an advancement in information accessibility is achieved. Beyond conventional ETAs, EOAs, and BEMS is the emerging technology of Sensory Substitution (SS). Through visually capturing the environment and translating this into an alternative sensory input, the novel potential to convey a high density of information to the user is realised. A limitation of SS technology is inability to deliver this density of information in a medium that can be processed by the user. Haptic, electro-tactile, and auditory systems have been shown to improve a visually impaired person's mobility capacity in controlled settings, although their use in realistic environments is still to be validated.

The shortcomings of these technologies can be attributed to the segregation of visually impaired research between medicine and engineering, preventing technology developers from accessing a complete set of user requirements. The mixed-methods approach of this thesis compiles the significant understanding of visually impaired mobility across these domains. This includes literature reviews in medicine and engineering, practical experimentation, and qualitative research. This results in the most comprehensive review of the visually impaired person's holistic mobility to date. A framework for designing mobility tools according to the processes of visually impaired mobility is therefore proposed, as follows:

1. Define user groups and measure baseline physiological and psychological processes, including individually and in crowds, through methods detailed in Chapters 3 and 5.
2. Draft generic requirements according to shortcomings in these fundamental processes.
3. Design a specific operational scenario in a realistic environment and quantify the multisensory features within that environment, detailed in Chapter 6.

4. Through practical experimentation, modify the environment for the optimum stimulation of residual vision as the first stage of intervention. Aim to minimise the likelihood of user dependence on personal mobility tools.
5. Where environmental augmentation cannot address user requirements, design mobility tools for the context considering both information required and its delivery.
6. Test mobility tools within these environments with each user over the short and long-term, specifically observing their quantified changes in walking behaviour and self-reported functional performance, detailed in Chapters 3, 5, and 6.

Finally, human behaviour models benefit from the improvement in understanding of visually impaired user requirements. Mobility data from the development of mobility tools must therefore iterate human behaviour models, and vice versa. Indeed, visually impaired people are likely to use these tools in the scenarios intended for modelling. These models can be:

1. Microscopic: Individual identified entities with the overall state of the system being defined by individual parameters and positions (Helbing, 2001). Examples include cellular automation, agent-based models, social force models, and particle swarm optimisation models.
2. Macroscopic: System described by Gross quantities typically dependant on space and time. Quantities obtained by local averages of the microscopic state (Hughes, 2003). Examples include queuing models and fluid-dynamic models.
3. Mesoscopic: Based on kinetic theory models – microscopic state of pedestrians still defined by individual position and velocity, but representation delivered by a suitable probability distribution over microscopic state (Bellomo, 2012).

A mesoscopic approach is ideally applied to modelling human behaviour, including that of visually impaired people. This is especially critical given the unique behaviours observed from visually impaired people in crowds in Chapter 5. Accomplishing a mesoscopic approach is difficult. This is because a visually impaired pedestrian's internal motivations and the external environment can affect the way in which they behave. Through exhaustively compiling these human, environmental, and technological factors, this thesis provides the foundations for the mesoscopic modelling of visually impaired mobility.

7.1.2. A Note on Mobility Outcome Measures

Mobility outcome measures are diverse and often differently employed across studies investigating visually impaired mobility. This diminishes the ability to compare between studies, especially given that any measures derived for an individual are functions of complex physiological and psychological processes, including comparisons between individuals of identical age, gender, and visual impairment. These include, but are not limited to, minute changes in visual function prevalent across identical eye diseases, knowledge of the environment, present (and often dynamic) cognitive state and mood, and any dependence on external mobility aids.

For example, comparing walking speeds in studies investigating visual field's impact on mobility would be unreliable, even in considering participants with similar visual disorders. Realistically, finding such studies proves impossible given that testing environments and participant samples vary drastically. In studies where participants are seemingly similar, the

participant groups described are often categorised by incomparable national standards, or through clinical measures without consideration of self-reported cognitive state.

Such remains true for the experimentation conducted in this study. As many experimental processes were as controlled as reasonable, including the mobility course design, lighting, and participant knowledge. However, the results observed from one participant could not be used to predict the quantitative performance of another. Instead, it was understood that the performance changes for VIPs was dependant on each VIP's visual function and cognitive state. This conclusion could only have been reached by observing the progression of the same sample of VIPs as group conditions were varied.

A best practice for observing visually impaired mobility is suggested; employ a highly individualised approach where changes across each individual are observed and then compared between individuals. In experimental settings, priority should be given to rigorous testing of each participant through greater repetition and prolonged testing, rather than solely maximising the number of participants.

For instance, in an experiment observing the impact of lighting on walking speed for participants with RP, conclusions on changes in walking speed can only be made when observing the same individual operating in two different lighting conditions. This is assuming all other factors remain identical. This can then be validated by repeating with other participants with similar characteristics, but not to quantitatively predict their behaviour at each lighting level. This change in approach is visually highlighted in Figure 7.3 and Figure 7.4 where the individual and 'group' (data collected from other experimental participants and external studies) are compared.

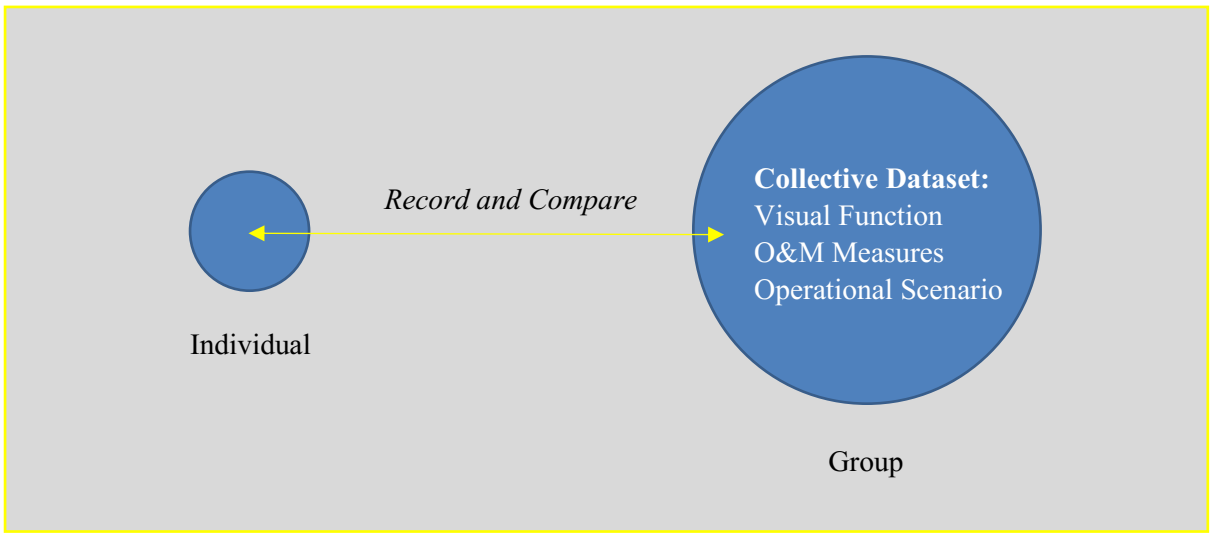


Figure 7.3: Predicting behaviour by observing group data.

Figure 7.3 highlights an unreliable approach to quantifying the mobility of a visually impaired person by comparing an instantaneous dataset to that collected from the group. Regardless of the volume of data gathered from these studies, the individual's mobility is a complex function of physiological and psychological processes that are difficult to control and dynamic in nature.

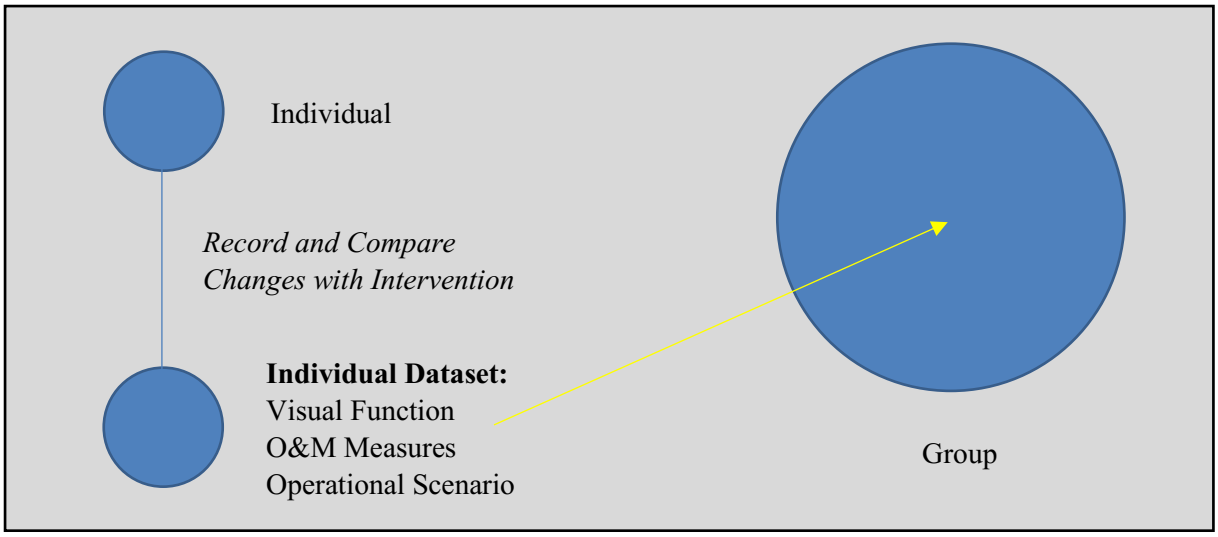


Figure 7.4: Predicting behaviour by observing changes across each individual.

Figure 7.4 describes an improved approach where experimentation is used to record changes in mobility resulting from controlled intervention (such as changes in environment). These changes are measured through each individual, prior to and following intervention. This can then be used to understand factors that positively and negatively impact mobility. Through more data collection and experimentation, the quantitative prediction of change on other visually impaired individuals is enabled.

7.2. Requirements for Navigation Systems for Visually Impaired People

7.2.1. Derivation of Requirements Aided by Subject-Matter Experts

A partnership formed between WeWALK, the Centre for Transport Studies at Imperial College London, and the Royal National Institute of Blind People (RNIB) on a project titled 'Developing, Implementing, and Verifying the Integrity of an Indoor Navigation System for Visually Impaired People'. The following requirements, derived in this thesis, were contributed for the system's development (Elhajj & Feghali, 2020). In this process, the requirements were augmented through semi-structured interviews with subject-matter experts from the RNIB, WeWALK, and Imperial College London throughout January 2021 (Spinks et al., 2021).

The project's outputs, including system architecture and experimental results enabled by this thesis, are detailed in Chapter 8. The following list headlines the organisation of requirements. For each, findings from the preceding literature reviews and experimentation were first input and consolidated. An open discussion followed in Spinks et al. (2021) where the requirements were reviewed, confirmed, and then added upon when needed.

1. Operation of a visually impaired user in navigation
- Tasks and subtasks
- Initial and active planning
- Progress
2. User motivation and mobility capacity
- Functional and recreational mobility
- Visual function and other factors affecting mobility capacity
3. System coverage

4. Items and routes
- Criticality, proximity, directionality, and interactivity
- Item parameters
- Route parameters
- User notification of items and routes
5. Environments and their features
- Generic environmental features
- Specific environmental features

Following this, an exemplification of these requirements in the design specification of the WeWALK smart cane and smartphone application is provided.

7.2.2. Tasks, Subtasks, and Progress

As discussed in section 7.1.1., a visually impaired person's successful journey is principled by completing tasks (macroscopic phases) and subtasks (microscopic phases). Navigation systems must operate on these principles through considering all tasks and subtasks within the user journey. In this context, only on completion of all subtasks within a task can the user move to the next task, as displayed in Figure 7.5. The generic subtask process in completing each task involves:

1. Accessing an entry or decision point
2. Obstacle detection, hazard awareness, orientation, and wayfinding ('Where am I?')
3. Accessing an exit point or transitioning to the next decision point

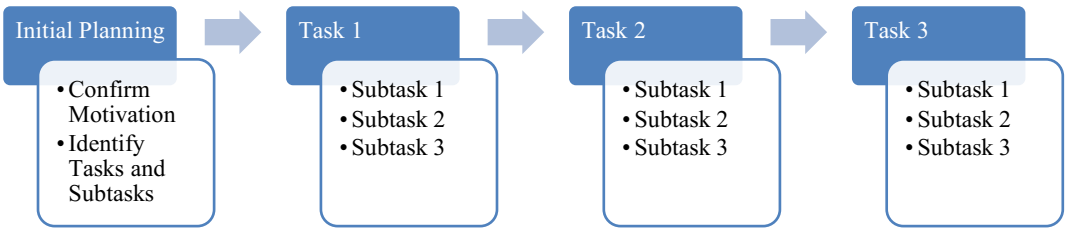


Figure 7.5: Tasks and subtasks in a user journey.

Journeys commence with initial planning to confirm motivation, and the ensuing task and subtasks. This is when the user will first interact with the navigation system. Active planning prevails throughout the entire journey according to changing motivations (internal decisions) and environmental factors (external decisions). Subtasks within a task may therefore change. More drastically, tasks may be eliminated or added if it becomes impossible or no longer desired to complete certain subtasks. The navigation system should allow for initial and active planning; this includes presenting the user with tasks in their journey (such as different transport modes), and subtasks (such as items and routes in each task).

Lewis et al. (2015) adds that, at any point during the journey, the user must be able to check on progress (COP). A COP is a primary component of active planning and should therefore be triggerable at all times. Spinks et al. (2021) suggest that this could be a user generated call, or

a predefined system alert scheduled according to the user's pre-set needs. The system should then return the user's current position, proceeding with one of two scenarios:

1. Correct position: Reassure the user that they are on the correct route.
2. Incorrect position: Guide the user to return to the correct route.

7.2.3. User Motivation and Mobility Capacity

Three generic user motivations are derived from Davies et al. (2012), and are expanded for the context of navigation, as follows:

1. Functional navigation: Critical tasks with time dependence. The system needs to classify and deliver information for the optimal completion of each task.
2. Recreational navigation: Optional tasks without time dependence. The system does not need to classify and deliver information according to a task.
3. Combination: A combination of critical and optional tasks. Critical tasks are prioritised, but optional tasks may be completed in between. The system needs to classify and deliver information for the optimal completion of each task.

Each will feature states of various user walking speeds; time criticality in each task is akin to an unrestricted or restricted scenario described in Chapter 5. In all scenarios, the system must allow for user instruction on the information to be classified and delivered. This can be according to the primary, secondary, and tertiary information classifications set out by Strothotte et al. (1996), Bradley and Dunlop (2004), or Lewis et al. (2015). These are described in Chapter 6.

To similar effect, mobility capacity will significantly impact how the user will interact with the system. This includes the spatial and temporal volume of navigation information required, and its user interface (Bradley & Dunlop, 2004; Lewis et al., 2015). Bradley & Dunlop (2004) has shown visual function to distinguishably alter the information requirements of visually impaired people according to the following categories:

1. Central vision loss (partially sighted)
2. Peripheral vision loss (partially sighted)
3. No useful vision (blind)

While as many system settings as possible must be customisable, these should aim to distinguish between these groups and offer pre-sets. For instance, blind users are likely to require more navigational cues than those with peripheral vision loss (Bradley & Dunlop, 2004). A system setting for more frequent navigational cues could therefore be enabled by default if such a blind user profile is defined. Other factors in mobility capacity can be considered including the capacity to physically mobilise; an example is the definition of wheelchair use where the system should automatically negate stair use (if such data is available).

7.2.4. System Coverage and Component Overview

Existing navigation systems for visually impaired people attempt to operate in either an outdoor or indoor environment, but not both. However, the completion of a task may require operation in a single 'catchment area' with indoor and outdoor environments. For instance, in the

(macroscopic) task of accessing an underground station, the user will need to conduct the following (microscopic) subtasks:

1. Locate the station and its entrance (outdoor)
2. Access the ticket hall and machines (indoor)
3. Find the correct platform and board their train (indoor)

It is therefore not optimal to designate a navigation system according to indoor or outdoor use. Rather, an ideal navigation system enables the user to complete every subtask in a desired task (or catchment area). The system should encompass a 'controlled' or 'uncontrolled' environment in which the system has or does not have coverage, respectively. Figure 7.6 illustrates this concept of system coverage where indoor and outdoor functionality is secondary to control.

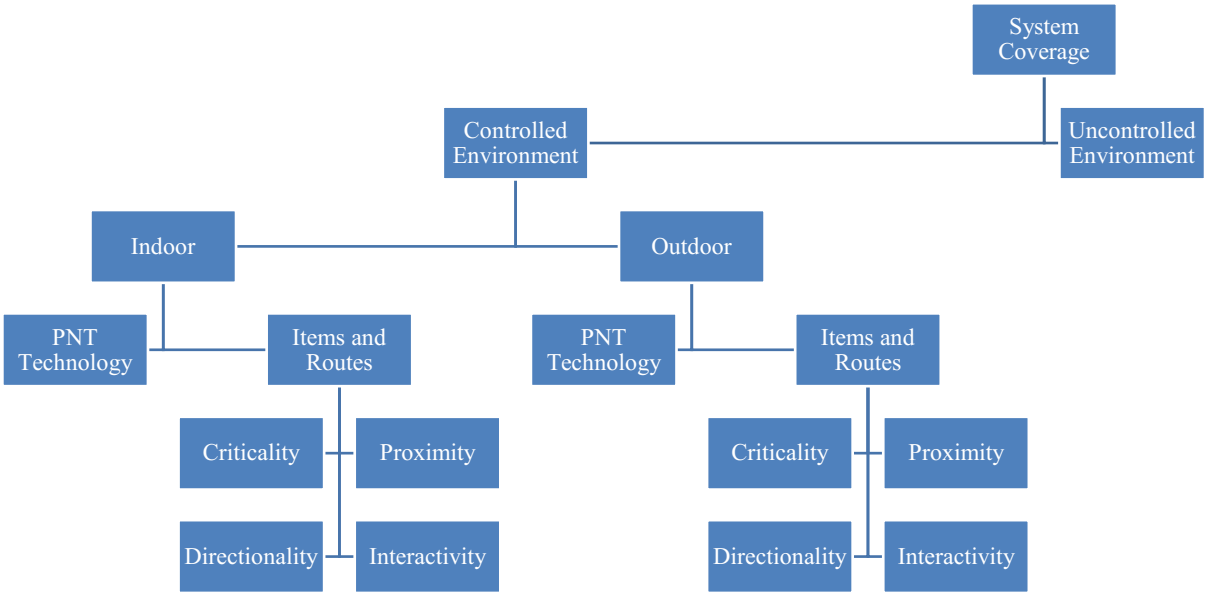


Figure 7.6: System coverage.

The user should be alerted when entering an uncontrolled environment, and that system functionality may be limited here. In controlled and uncontrolled environments, the system should account for the information it provides, but not be liable for users' proceeding actions. For each indoor and outdoor setting, the appropriate Positioning, Navigation, and Timing (PNT) technique should be employed according to the items and routes that the user may interact with. For instance, detecting a platform edge will require greater PNT accuracy, precision, and safety-criticality than detecting a shop front.

7.2.5. Items and Routes

7.2.5.1. Introduction to Items and Routes

Items (also termed Points of Interest (POIs) or nodes), and the routes (or tracks) connecting them are the two fundamental components of a navigation system (Loomis et al., 1998; Lewis

et al., 2015). An item is an object that a user would interact with, cognitively or physically. This could be an environmental feature (such as an escalator), or a decision point (such as boarding a transport vehicle). Through a journey, the user may interact with several items along several routes.

First examined by Strothotte et al. (1996), items and routes present different accessibility, usability, and priority to visually impaired people. Items and routes should therefore incorporate their own unique parameters. Parameters may be defined according to system pre-sets, user input, or an Application Programming Interface (API). These enable the system to discern the criticality of items and routes for the completion of tasks and subtasks. Items and routes must have the following core parameters:

1. Criticality (Strothotte et al., 1996; Sanchez & Maureira, 2007)
2. Proximity (Loomis et al., 1998; Loomis et al., 2001)
3. Directionality (Loomis et al., 1998; Loomis et al., 2001)
4. Interactivity (Spinks et al., 2021)

7.2.5.2. Item Parameters

Spinks et al. (2021) elaborate upon item parameters through subparameters as follows (Table 7.1):

Parameter	Description	Recommended Format
Criticality		
Coverage	Within bounds of the user's operational area (such as excluding an arrivals lounge from a user operating in a departures lounge)	Binary (yes/no)
Task	Priority according to the user's journey (such as a platform on a train journey)	Binary (yes/no)
Status	Operational availability of the item (such as a lift being out of order)	Binary (yes/no)
User	Usage according to user ability and preference (such as stairs to a wheelchair user)	Binary (yes/no)
Misc.	Identify a change in the item	String
COP	Trigger when COP	Binary (yes/no)
Priority	Critical item that is always announced	Binary (yes/no)
Proximity		
Speed	Speed at which user is approaching item	Numeric
User	Distance between user and item	Numeric
Alert	Distance at which user is alerted to item	Numeric
Directionality		
User	Item location according to the user's heading/bearing/course	Numeric
Interactivity		
String	Instruction to user on how to interact with item	String

Table 7.1: Item parameters and subparameters.

7.2.5.3. Route Parameters

Route criticality, proximity, directionality, and interactivity are primarily dependant on those for items. For instance, if an item is not critical to the user, then neither is the route. Similarly, the user directionality of the route is dependent on the directionality of the user to the item. Spinks et al. (2021) suggest additional route subparameters as follows (Table 7.2):

Parameter	Description	Recommended Format
Criticality		
Coverage	Within bounds of the user's operational area (such as excluding an arrivals lounge from a user operating in a departures lounge)	Binary (yes/no)
Mapped	Mapping availability for route	Binary (yes/no)
Mode	Differentiate between travel mode	Discrete (stationary, walking, vehicle)
Status	Operational availability of the route (such as a walking path under construction)	Binary (yes/no)
User	Usage according to user ability and preference (such as routes with stairs to a wheelchair user)	Binary (yes/no)
Misc.	Identify a change in the route	String
Proximity		
Speed	Speed at which user is approaching or using route	Numeric
User	Distance between user and route	Numeric
Alert	Distance at which user is alerted as off-route	Numeric
Directionality		
User	Route heading according to the user's heading/bearing/course	Numeric
Geometry	Quantitative description of route shape (such as turnings and distances between them)	Numeric
Barriers	If and where a barrier is located along the route	Binary (yes/no) and Numeric
Interactivity		
Definition	Type of space (such as an open outdoor space, indoor shopping centre, etc.)	String
Surface	Qualitative description of incline and shape (such as uphill or downhill, asphalt or grass)	String
Dynamic	Dynamic elements (such as if a surface is wet)	String
Crossing	Crossing or interaction with other items along route	Binary (yes/no) and String (item name)

Table 7.2: Route parameters and subparameters.

7.2.5.4. User Notification of Items and Routes

Spatial organisational principles form the final part of the knowledge hierarchy required for effective mobility capacity (Passini et al., 1990). Upon conducting a COP, the user may then wish to learn about items and routes that are not within the bounds of their journey. This feature must be constantly available, regardless of task or system coverage (if available).

The core parameter of criticality for items and routes is defined as primary, secondary, or tertiary according to the combination of its subparameters. The thresholds for each should be pre-set by the system or user, affecting how the user is notified:

1. Primary: Notify user – Critical
2. Secondary: Notify user - Additional information
3. Tertiary: Do not notify user

External influence should be able to affect items and routes, particularly human input and external APIs. For instance, users may wish to label locations and preferential routes for breadcrumbing. Users could then choose to allow other users access to these routes. Another use-case is integrating transport operator APIs to direct users away from congested or closed transport modes. However, data reliability and availability may be constrained in these scenarios, and such functionality should only be enabled when data limitations are overcome. For instance, user ratification and moderation could mitigate the risk of users sharing intentionally incorrect data.

Finally, the delivery of item and route information should occur through auditory or haptic feedback, or both. Classical speech-based navigation cues must be available given high likelihood of user acclimation through existing applications. Likewise, the use of haptic feedback for obstacle detection is widely applied. Haptic feedback may be used standalone for users who do not prefer auditory feedback (including hearing-impaired users), or to supplement auditory cues. Additionally, the system could consider emerging interaction methods including Earcons and Spearcons, described in Chapter 6.

7.2.6. Environments and their Features

7.2.6.1. Generic Environmental Features

Generic environmental features are items and route characteristics that a user will interact with that are not specific to a defined environment. Entrances, exits, stairs, and toilets are examples of such. Generic items listed in the Wayfindr (2018) standard, and route characteristics described by Fernando et al. (2019) and the National Research Council (1986) are utilised as a foundation. These are the only studies to discuss item and route parametrisation for visually impaired navigation in the reviewed literature. Other features are added according to intuition and recommendation by Spinks et al. (2021).

Table 7.3 includes requirements for generic environmental features. Here, a literature gap is defined as a concept not considered in literature. They are important as they could affect mobility performance, as discussed in Chapters 3, 5, and 6. Requirements are classed as being either ‘hard’ (essential) or ‘soft’ (desirable or ideal), as suggested by Strothotte et al. (1996). They describe how navigation systems can address current gaps and are contributed by Spinks et al. (2021).

Feature	Literature Gap	User Requirement	
		Hard	Soft
Entrance/ Exit	- Entrance/exit type (such as a revolving or push/pull door)	- Accessibility of entrance/exit according to user ability - Usability as an entrance, exit, or both	- Prerequisites to accessing these (such as a key card)
Pathway	- Walking position (left/right) in one-way systems - Texture and gradient	- Directionality and walking position	- Texture information for initial user planning
Crossing	- Length of crossing - Green time	- Controlled, uncontrolled, or spontaneous crossings	- Length of crossing - Green time
Decision Point	- Accessibility according to user ability - Emergency egress scenarios	- Accessibility of decision point according to user ability	- Egress routes and nearest exit upon alarm
Tactile Surfaces	- Variability and inconsistency of existing tactile surface standards and applications	- Do not identify tactile surfaces to the user	- Surface textures, such as a smooth surface, to indicate entry points and routes
Escalator	- Escalators may change movement direction (up/down/static) - Up/down/static escalators may vary in position	- Escalator movement direction - Escalator position	- Escalator width as a user preference - Handrail position - Distance to landing
Stairs	- Stairs incorporate different tactile surfaces and edges - Navigating stairs is a repeated action forming tacit knowledge	- Do not identify number of stairs or tactile surfaces	- Availability of handrail and its position - Head height obstacles or landing height - Alert for open riser staircase
Lift Lobby	- New lifts with a centralised lift call	- Number of lifts - Route guidance to the arriving lift	- Connections between lift systems (call lift)
Required Lift	- Not considered in Wayfindr (2018) standard	- Positioning and ordering of buttons	- Presence of an accessibility button
Toilet	- Not considered in Wayfindr (2018) standard	- Toilet type and accessibility (such as a changing places toilet)	- Locks or interactivity (such as a radar key or code)
Queuing Point	- Not considered in Wayfindr (2018) standard	- Queuing point structure (structured/unstructured)	- Typical queue length
Gateline	- Span of gateline and position of entry/exit gates	- Span of gateline and position of entry/exit gates	- Points at which not to stand or wait
Platform	- Platform width - Seating location - Shelter availability - Help point location	- Platform width and edge warning - Seating location - Help point location	- Shelter availability - Customer information display location - Availability of platform edge doors - Illumination level

Table 7.3: Generic environmental features.

7.2.6.2. Specific Environments

The system must aim to operate in as many different environments as possible. While each environment will contain generic items and routes, visually impaired people will encounter challenges specific to that unique environment that the system should help to overcome. For instance, identifying the boundaries of an open space, or determining the correct platform in a

through station. The following is a list of environments for system operation, compiled through an intuitive process with contribution and review from Spinks et al. (2021). This is intended to be as exhaustive as possible, although other environments may be added by navigation systems when identified.

1. Outdoor (general)
2. Indoor (general)
3. Street
4. Open space (park, beach)
5. Shared space
6. Bus stop
7. Bus terminal
8. Taxi rank
9. Through station
10. Terminating station
11. Airport
12. Shopping centre
13. Commercial unit
14. Restaurant/Eatery
15. Hospital
16. Local clinic
17. Public house
18. Museum
19. Theatre/Cinema
20. Stadium
21. Office/University building
22. Private dwelling
23. Gym
24. Sports hall
25. Hotel
26. Miscellaneous

In transitioning between environments, the system must distinguish the environments and notify the user immediately. Miscellaneous environments are those not considered within this list; here, the system may default to a reduced or generic functionality. A critical literature gap identified in Chapter 6 is that research on the challenges and requirements for visually impaired people when navigating in different environments has not been compiled. Particularly, research with a consistent visually impaired sample investigating behaviours across environments has not been found. To address this, rigorous interviews with a fixed sample of VIPs and NSPs was conducted during system testing, detailed in Chapter 8. This novel experimentation provides insight into the different requirements of a user when transitioning between environments.

7.2.7. Exemplary Design from the WeWALK Smart Cane and Smartphone Application

7.2.7.1. Introduction to the WeWALK Smart Cane Hardware and Integration with Software

WeWALK (2022) has created a novel smart cane and companion smartphone application to address shortcomings in existing ETA and EOA designs. The smart cane is an attachment that

fits on top of a white cane, replacing the existing handle, but maintaining standard cane usage techniques. Displayed in Figure 7.7, the WeWALK smart cane's external components comprise of:

1. Wrist strap hole
2. Soft-touch grip
3. Tactile buttons
4. Touchpad
5. Ultrasonic sensor
6. Front LED
7. White cane adaptor
8. White cane insertion hole
9. Micro USB port
10. Microphone
11. Power button
12. Speaker

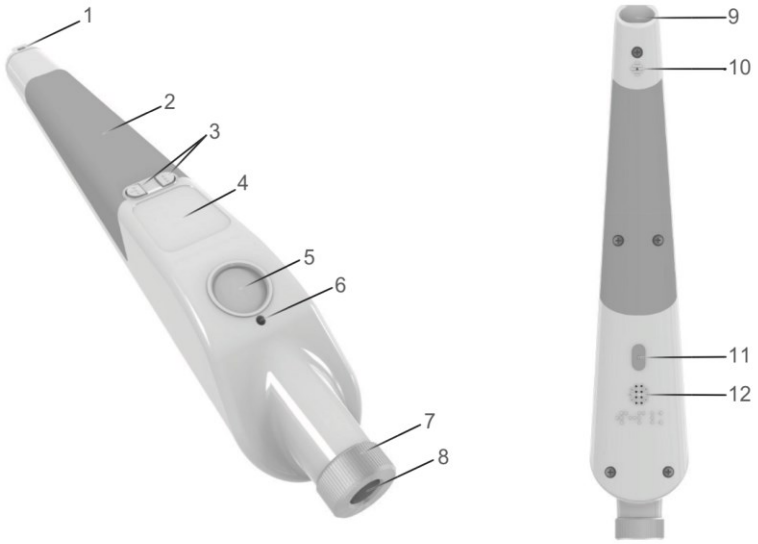


Figure 7.7: WeWALK smart cane attachment.

Internally, the smart cane attachment houses a lower-power microprocessor (and associated PCB components), battery, vibration motor, Bluetooth adaptor, and an Inertial Measurement Unit (IMU) comprising a three-axis gyroscope, accelerometer, and compass. WeWALK's operating principle is that the user can obtain:

1. ETA functionality through above-ground obstacle detection using the ultrasonic sensor and haptic feedback (adjustable detection distance from 80 cm to 165 cm).
2. EOA functionality through connectivity to a smartphone, the WeWALK smartphone application, and its integration with mapping APIs. This allows for auditory turn-by-turn walking and public transport guidance via the inbuilt speaker or headphones. The smart cane hardware facilitates smartphone control through touchpad gestures and auditory interaction. Alternatively, the application can be controlled through the smartphone via a user interface with customisable accessibility options.

3. Standard white cane use to maintain ground surface, obstacle, and drop-off detection (Figure 7.8).



Figure 7.8: WeWALK smart cane in use.

This novel combination of features designates WeWALK as a Binary Electronic Mobility System (BEMS) (Feghali et al., 2021). Furthermore, the adoption of smartphone connectivity allows for continuous development and updated mapping data. This enabled the requirements derived through this thesis to form the design specification for the WeWALK smartphone application's overhauled user interface and navigation engine (WeWALK application version 2) (Feghali et al., 2021; WeWALK, 2021). This was then delivered to the WeWALK software development team for coding, implementation, and distribution. The translation of requirements to an at-market product is exemplified and recognised by the Royal Institute of Navigation (RIN) through the W.G.P Lamb award for a major contribution to a more navigable world by a younger person (Royal Institute of Navigation, 2021).

7.2.7.2. Application Interface

Different visual functions are considered by allowing users to select from a range of high contrast and text size options (Figure 7.9) (WeWALK, 2021). High contrast options include black elements on white backgrounds, white elements on black backgrounds, or yellow elements on black backgrounds. This accounts for users with reduced contrast and colour sensitivity, including yellow text for those with photophobia or glare sensitivity. Visual acuity is accounted for through text sizes that can be varied across the entire application. Additionally, full screen reader compatibility enables access for users without usable vision.

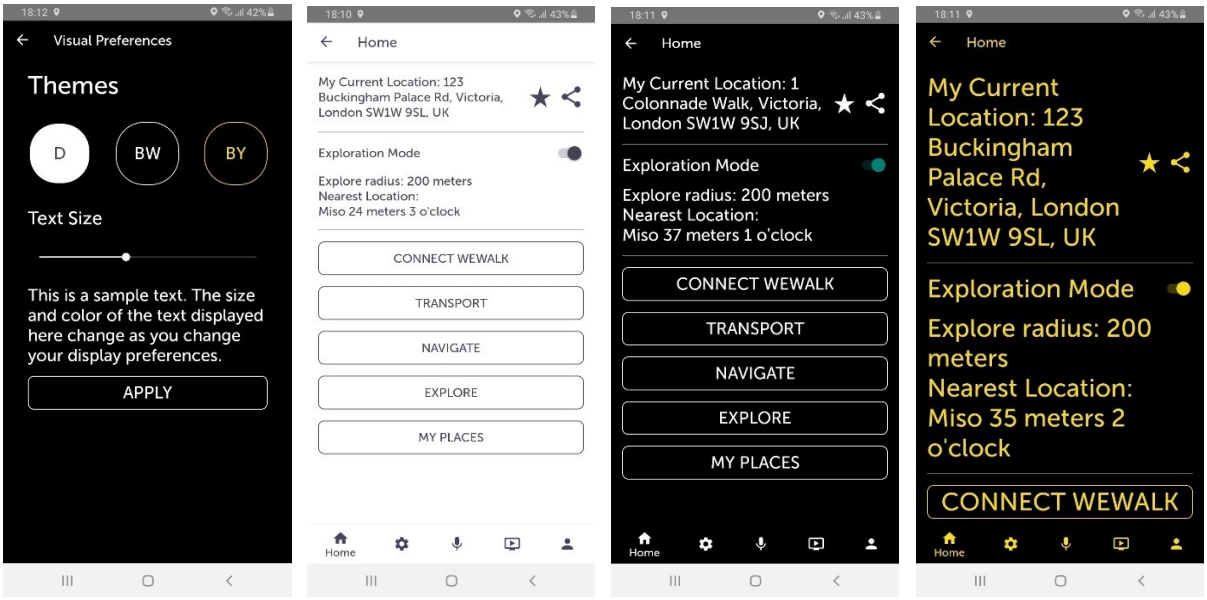


Figure 7.9: WeWALK application interface (WeWALK, 2021).

7.2.7.3. Multimodal Navigation

WeWALK incorporates walking and public transport navigation through integration with the Moovit (2022) API. Walking navigation operates on the node and path principle where the user is alerted to both the path and node's directionality and proximity to them. Figure 7.10 describes this user interface (WeWALK, 2021). The user is informed of their next node (task), the direct path distance to it, it's directionality relative to the user's heading, percentage completion, and step-by-step instructions to reach it along the walking path. The walking path is comprised of several sub nodes (subtasks), and updates according to the user's heading. In the example from Figure 7.10, 'head your 9 o'clock' instructs the user to shift their heading 90 degrees to the left to proceed on Bulleid Way. A visual route map with high contrast polyline and map is also provided for users with usable vision.

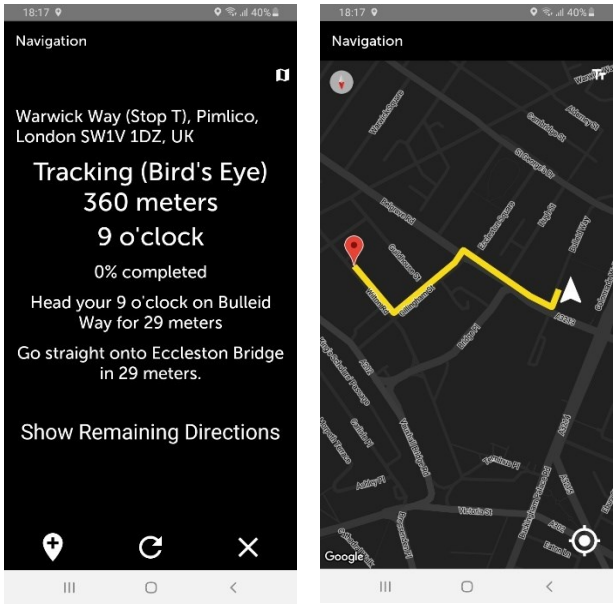


Figure 7.10: WeWALK walking navigation (WeWALK, 2021).

The next walking path sub node is defined when:

1. There is a turning in the road leading onto a different road
2. A road is crossed onto a different road (only if the road name changes)
3. There is an off-ramp or an irregular road feature such as a set of stairs

Customisation options include the measure of directionality (cardinal or clockwise), and the distance or time interval at which the user is auditorily alerted of navigation progress and instructions. All auditory feedback can also be disabled. A chime is used prior to the delivery of the navigation information through Text to Speech (TTS). The TTS engine used is at the operating system level and can therefore be customised by the user in its language, pitch, speech rate, and other engine-specific settings. Figure 7.11 presents the process of delivering auditory navigation information to the user, when enabled.

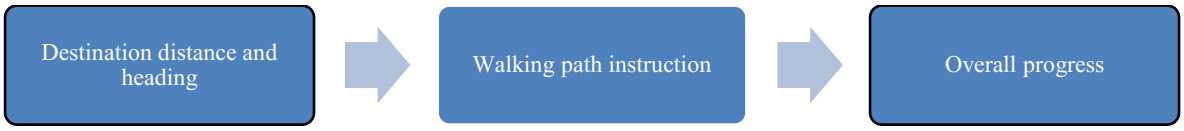


Figure 7.11: Process of delivering auditory navigation information to the WeWALK user.

In the walking navigation example from Figure 7.10, this constitutes to the following instructions being auditorily delivered to the user (Figure 7.12):

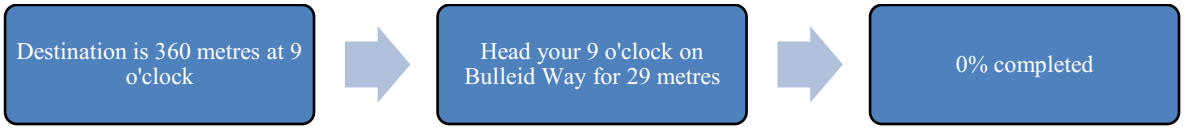


Figure 7.12: Example of delivering auditory navigation information to the WeWALK user.

All instructions are repeated according to the distance or time interval preferred by the user, providing explicit knowledge when needed to mitigate sensory overload. To similar effect, touchpad gestures can be used to COP, triggering specific auditory information. Figure 7.13 displays the function of swipes on the WeWALK smart cane's touchpad during navigation for COP.

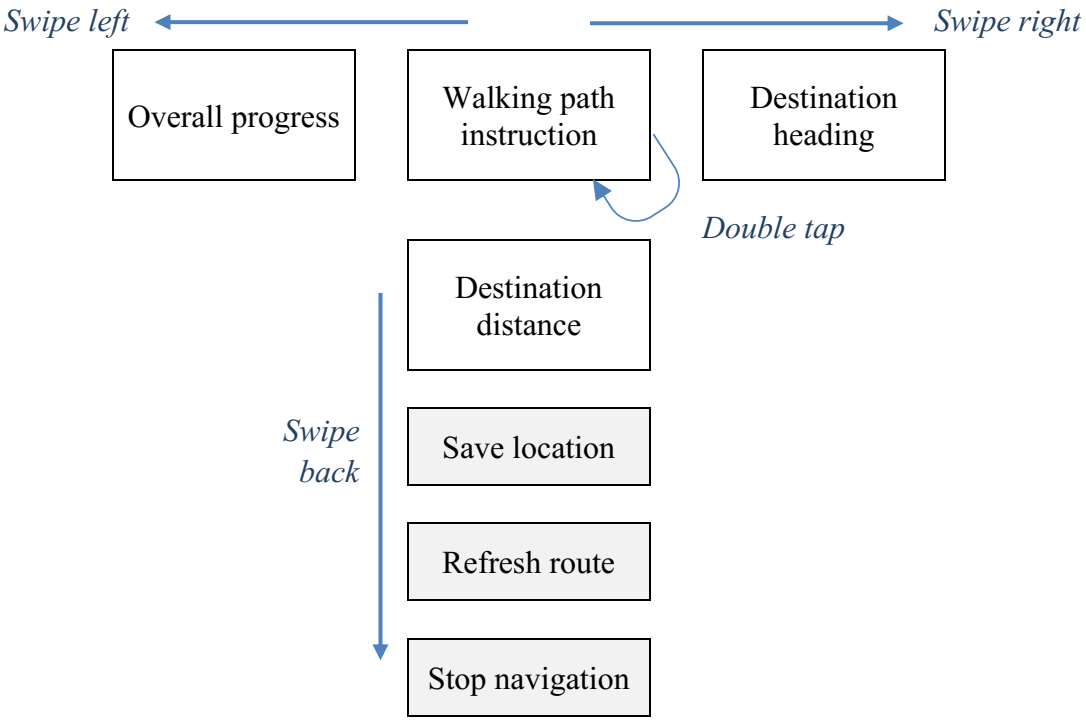


Figure 7.13: COP process for triggering auditory feedback using the WeWALK smart cane's touchpad during navigation.

Figure 7.14 displays the public transport feature built into WeWALK utilising the Moovit (2022) API (WeWALK, 2021). Transport modes are categorised, and their respective stops and timetables are displayed. Upon selection of a stop, mode, and vehicle number, the stops at which the vehicle calls at are displayed, and a particular stop can be tracked according to user preference. This forms the user's primary knowledge required to board and alight the correct vehicle at the correct stop. Additionally, the organised provision of transport information contributes to secondary and tertiary knowledge; a requirement for proficient transport use, as found by Sanchez and Maureira (2007).

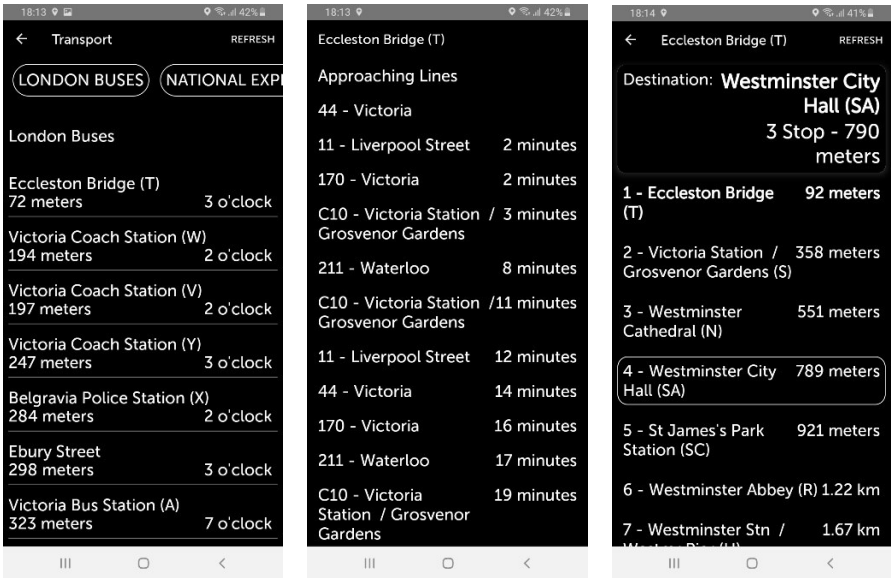


Figure 7.14: WeWALK public transport integration (WeWALK, 2021).

A shortcoming of navigation systems designed for visually impaired people is insufficient integration of public transport and walking navigation into a single multimodal journey. Particularly, an overview of transport modes (tasks) and the subtasks required to access them is not provided. This is especially problematic given the importance of initial and active planning for users. To address this, a multimodal navigation system operating on the task and subtask principle is designed and implemented in WeWALK, as shown in Figure 7.15 (WeWALK, 2021).

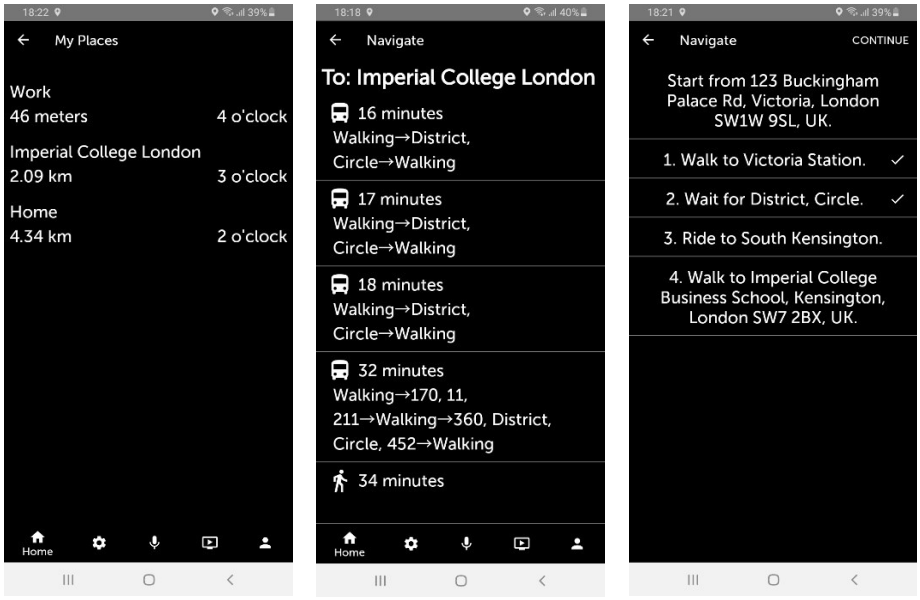


Figure 7.15: WeWALK multimodal navigation (WeWALK, 2021).

Upon searching for a destination or selecting from a list of saved places, journey suggestions are provided prior to the journey starting. Following user selection of their preferred journey, the detailed journey plan is displayed where all tasks and subtasks may be previewed. This is intended to fulfil initial planning requirements. A navigation process is triggered for each task in order, and tasks cannot be skipped unless explicitly forced by the user. Considering the example in Figure 7.15, an instance of walking navigation to Victoria Station is triggered on journey start. The user is presented with the walking navigation interface from Figure 7.10 and, on completion, the next task in the journey is triggered where a list of District and Circle line trains is presented. The required stop (South Kensington) is then tracked upon boarding the relevant vehicle through an interface similar to that in Figure 5.14.

Throughout, COP is triggered periodically by the system, or when needed by the user via touchpad gestures or direct interaction with the smartphone interface. This novel application of multimodal navigation compartmentalises the user journey, allowing for the user to reroute subtasks according to internal or external factors. Compatibility with active planning is therefore ensured. However, the quality and availability of transport accessibility data remains in the API's control; the user may not have access to sufficient information for effective planning when API data is unavailable.

7.2.7.4. Exploration

An exploration mode is present throughout the entire journey to address the user's recreational or functional motivation. Two methods of accessing this service are provided according to a

recreational or functional bias, respectively. The first is an automated notification of nearby items triggered by a single enable/disable button on the WeWALK application's main screen. The second is a dedicated exploration page with a list of items (Figure 7.16) where users can seek additional information including saving, contacting, and navigating to items (WeWALK, 2021). Enabled by integration with the Foursquare API, nearby items are categorised according to:

- Arts and Entertainment
- Food and Cafes
- Professional Services
- Shops
- Schools and Universities
- Fitness and Wellness
- Pubs and Clubs

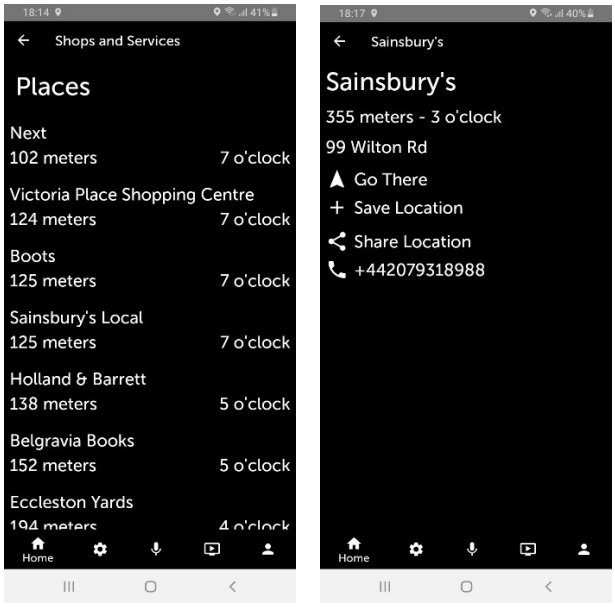


Figure 7.16: WeWALK exploration feature (WeWALK, 2021).

The user must receive sufficient information to identify a nearby item without excessive detail, repetition, or disorientation. This is a critical design requirement during navigation. To address this user requirement, the following design decisions are made:

1. Customisable notification settings for item category and timing.
2. Automated distance optimisation in instances where too many or too little items are within a pre-set radius.
3. A touchpad gestures or interface toggle to immediately enable or disable item notifications during navigation.

Figure 7.17 describes the process for which a user is auditorily notified of a nearby item through TTS.



Figure 7.17: Process of delivering auditory exploration information to the WeWALK user.

Considering the example in Figure 7.16, the auditory feedback for the first item would amount to the following (Figure 7.18):

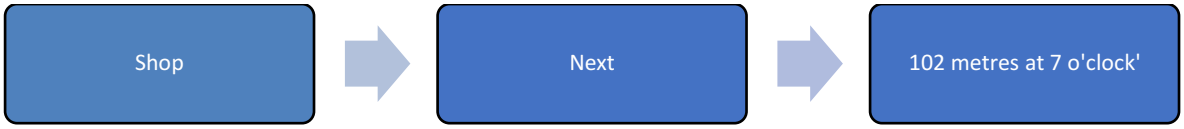


Figure 7.18: Example of delivering auditory exploration information to the WeWALK user.

7.2.7.5. Mobility Tracking

A fundamental conclusion from this thesis is the deficiency of long-term data on the mobility of visually impaired people in realistic operational scenarios. This is shown to extend to the availability and comparability of clinical research data in Chapter 3 (Rubin et al., 2010; Spark Therapeutics, 2019). The quantifiable effects of rehabilitation, orientation, and mobility training on a visually impaired person therefore remain largely unknown. It is therefore proposed and implemented that the WeWALK smart cane's IMU be used, in conjunction with smartphone positioning data, to track mobility through daily usage. A concept design for this system is produced in Figure 7.19 and its development is underway in collaboration with Microsoft (Lanxon, 2021; Microsoft, 2021).

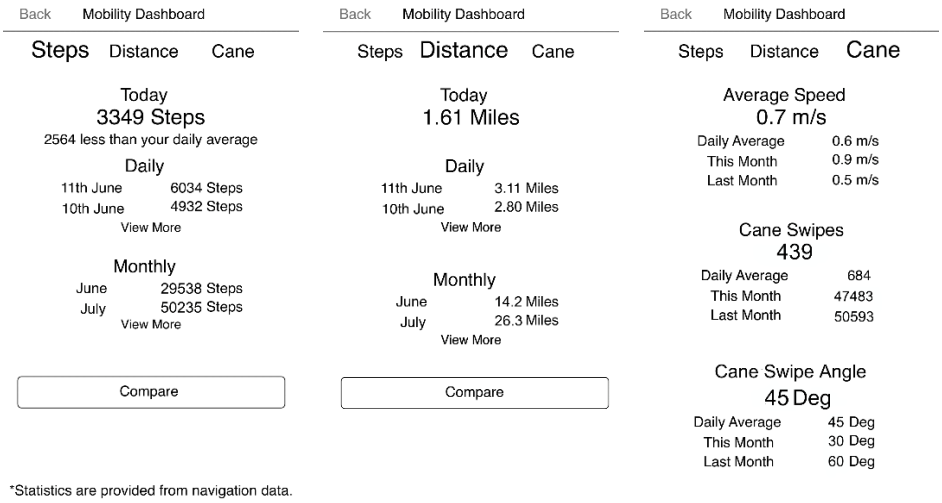


Figure 7.19: WeWALK mobility tracking home interface.

As inputs, the system queries the user on their visual function, asking for a diagnosis of visual impairment, visual field reduction, visual acuity measures, and whether or not the user is photophobic and has poor contrast sensitivity. The system concept includes the measurement of the following functional performance metrics:

1. Walking speed
2. Time spent mobilising independently in different environments
3. Cane motion metrics including swipe width, swipers per step, and the cane's angle to the ground
4. Self-reported confidence ratings to correlate physiological data with the user's psychological state

Figure 7.20 describes how self-reported confidence input is collected following every journey detected by the system. A journey is defined according to in-development system logic incorporating minimum time and distance conditions. Operation in new environments and crowds is queried following the correlation between familiarity, crowd performance, and mobility derived through this thesis. Ultimately, through long-term data collection of the same user's mobility performance, the principle described in Figure 7.4 is realised. A holistic overview of the factors affecting mobility, including changes in visual function, can therefore be derived. The envisioned benefits of such a system include improvements in human behaviour modelling, the provision of healthcare and clinical research, and the development of mobility aids for visually impaired people.

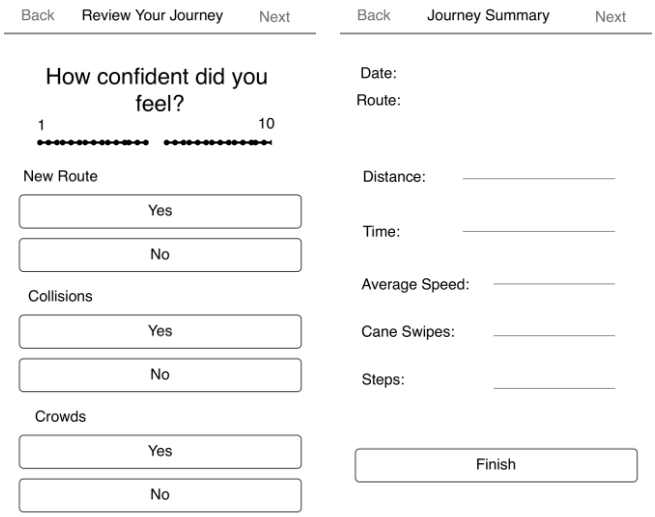


Figure 7.20: WeWALK mobility tracking data entry post-journey concept.

7.2.7.6. Limitations of the WeWALK System

Primarily, the WeWALK system is bound by the data that is made available to it; navigation data is provided by external APIs, as is item and public transport information. Moreover, the connected smartphone's GPS underpins WeWALK's PNT. WeWALK therefore only operates in outdoor settings without control of data availability or reliability. The hardware device is cane-based, and this may not meet the requirements of guide dog users, or those that do not prefer to use a cane. Other shortcomings include limited waterproofing, and the reduced functionality of ultrasonic sensing in wet conditions. Notwithstanding, the combination of ETA and EOA functionality is novel, providing a suitable development platform for other PNT and data sources.

7.3. Summary of Findings and Proceeding Development

This chapter consolidates findings from the literature reviews and experiments conducted in this thesis thus far to summarise requirements for visually impaired mobility. The causal factors within mobility capacity are first listed. These are then linked to the environmental and technological augmentations that constitute mobility performance. Following this, recommendations are made for the use of mobility outcome measures when assessing visually impaired mobility. The requirements for visually impaired navigation are proposed with aid

from subject-matter experts, including integration into the WeWALK system's current feature-set.

However, this system is intended for outdoor use, and therefore does not meet the requirement of indoor and outdoor availability in the user journey. To address this, these requirements are contributed to the development of WeWALK's indoor feature-set in collaboration with Imperial College London and the RNIB. The translation from user requirements to the functional system architecture are discussed in the following chapter (Chapter 8), including practical experimentation to validate system functionality and identify shortcomings.

8. Developing and Validating a Navigation System to Improve Visually Impaired Mobility

Following the definition of visually impaired user requirements in Chapter 7, this chapter discusses their contribution to the development of an indoor navigation system in partnership with Imperial College London and WeWALK. This includes practical experimentation and validation. Section 8.1 introduces the project, while section 8.2 describes the system functionality derived from the user requirements. Section 8.3 begins with a summary of the system's preliminary testing, proceeding with the methodology, results, and discussion of practical testing with visually impaired participants. The findings from this thesis are shown to holistically benefit system development, from provision of requirements, execution of an effective experimental methodology, and validation of these requirements. Finally, limitations and recommendations are provided for future system iteration.

8.1. Introduction to the Project Objectives and Experimental Methodology

The requirements derived through this thesis confirm that orientation and mobility issues continue to inhibit visually impaired people. Safety-critical obstacle detection and wayfinding in all environments are primary pain points that have not been sufficiently addressed by environmental and technological augmentation. This is as the unique walking environments occupied by visually impaired people are difficult to standardise. Limited research and international agreement on an optimum standard further exacerbate this.

In response, ETAs and EOAs have been developed to improve the user's own functional ability. However, commercially available solutions remain limited in that none have addressed both pain points in indoor and outdoor spaces. It is only through novel developments in the WeWALK smart cane, launched in 2019, that the function of an ETA and EOA have been combined into a single electronic aid, termed a BEMS. Limitations prevail in that it can only position a user outdoors through GPS, and cannot position the user indoors (Feghali et al., 2021).

To address the challenges inhibiting the use of the WeWALK smart cane in indoor spaces, WeWALK formed a partnership with the Centre for Transport Studies at Imperial College London and the Royal National Institute of Blind People (RNIB) while sub-contracting Astra-Terra, a London-based SME specialising in developing intelligent transportation systems. The consortium successfully obtained grant-funding through UKRI's Innovate UK smart grant and commenced a collaborative 18-month-long project in October 2020 titled 'Developing, Implementing, and Verifying the Integrity of an Indoor Navigation System for Visually Impaired People' (Elhajj & Feghali, 2020).

This thesis contributed the user requirements for this system, aided by subject-matter experts from the project consortium (discussed in Chapter 7). These developments governed the system-level requirements and, in turn, the Positioning, Navigation, and Timing (PNT) specification. The integrated inertial sensors in the WeWALK smart cane were paired with low-cost Bluetooth Low Energy (BLE) beacons. This was to be augmented by signals of opportunity (SOOP), such as 5G and GNSS measurements, when available. Integrity monitoring was a novel addition with the intention of assessing PNT availability and precision.

The PNT system development was led by Imperial College London and Astra-Terra (Alghananim et al., 2022). As a critical component of this thesis and the project, user testing of the system was then conducted at Imperial College London. The extent to which the requirements were captured by the system was assessed. Iterations were then suggested, exemplifying the holistic application of this research throughout the development lifecycle. Moreover, the practical implications of this thesis' findings on enhancing the PNT domain were confirmed.

The project close-out concluded on 7th April 2022 following successful completion of all work packages. It should be noted that the project timeline and funding limited the scope of hardware and software implementation; hardware components were restricted to Bluetooth and IMU (as present in WeWALK's first commercially available hardware version, the current version at the time of the project). Consequently, it was not possible to develop positioning through emerging technologies such as UWB or computer vision given the higher associated costs. Future iterations of the WeWALK system may therefore address additional user requirements as commercial viability improves.

8.2. System Architecture Derived from User Requirements

The user requirements contributed by this thesis enable the creation of a functional system architecture for the positioning and navigation of a visually impaired person in all environments (Elhajj & Feghali, 2020). As the project addresses indoor navigation, the indoor positioning system architecture could then be specified by a hierarchy of four levels, as expanded by Alghananim et al. (2022). These are described as follows:

1. Functional system architecture: Identifies the functions to satisfy the user requirements. This is the overall architecture with the aim of overviewing the macroscopic components of the user journey in all environments.
2. Positioning and localization function: Specifies the generic positioning and localisation function presented as part of the functional system architecture, including proposed positioning systems, in generic environments indoors, outdoors, and in the transition between indoor and outdoor environments.
3. Indoor positioning function: Details the positioning architecture proposed for indoor environments comprising Bluetooth and Inertial Measurements Units (IMU) integration.
4. Sub-architectures of the indoor positioning function: These detail specific system components including Bluetooth anchor calibration and the extended Kalman filter integration in the proposed Bluetooth and IMU positioning.

8.2.1. Functional System Architecture

Figure 8.1 denotes the functional system architecture for the positioning and navigation of a visually impaired person, building on Elhajj and Feghali (2020). The architecture comprises of three key components of the user journey:

1. Planning the journey
2. Real-time detection during a journey
3. System communication allowing for active planning and system interrogation.

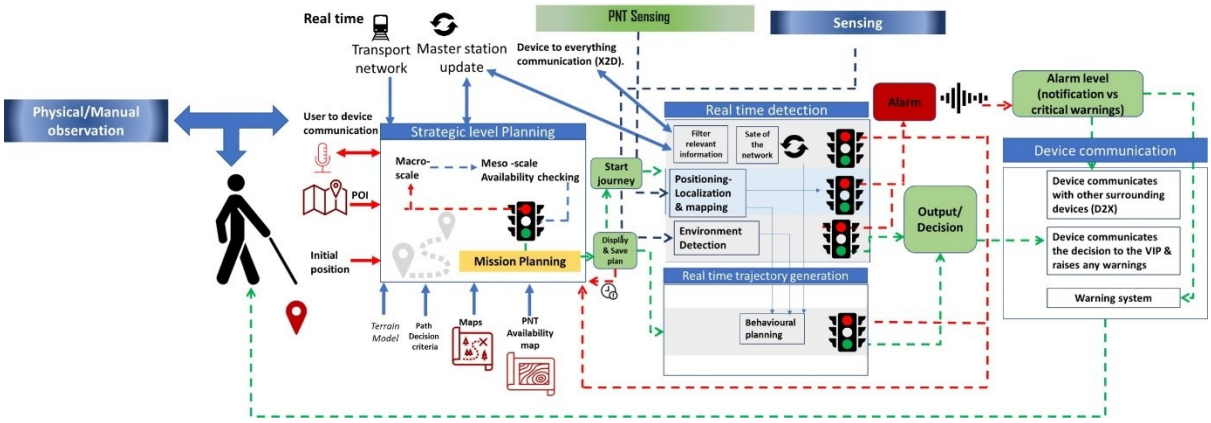


Figure 8.1: Functional system architecture for visually impaired positioning and navigation.

The user will primarily conduct and input their own observations throughout the journey, determining their use of the positioning and navigation system. The hierarchy governing this is detailed in Chapter 3. This includes physiological and psychological components according to whether the user is behaving individually or as part of a crowd; namely, the user's capacity to detect the environment, capacity to physically mobilise, knowledge, cognitive state, capacity to detect the crowd, physical forces from the crowd, and their self-awareness and social awareness. For instance, in an unfamiliar environment, the user's dependence on the system will likely increase as the planning phase is extended. System interrogation may also occur more frequently during their journey.

Following initial user observation, the mesoscopic strategic plan can then proceed incorporating the macroscopic and microscopic tasks within the user journey, and the user's motivation of either purposeful or freeform navigation, or a combination of both within these. Several inputs from both the user and the system will be required at this stage, primarily the user-device communication preferences and any changes according to the particular mobility scenario (such as modifications to the mobile application's visual and voice interface depending on how often the user seeks the system's guidance), the user's destination (or lack thereof in freeform exploration), and the user's current location. Wider system inputs will then determine the optimal user journey to feedback to the user for approval or further planning.

As the visually impaired user will likely have specific transport and environment preferences, the system must therefore poll several internal and external data sources to deliver a safe and feasible journey according to the user's default or newly-input criteria. These include data from transport provides on timetables and station infrastructure (such as step-free availability, station lighting, and help-point locations), internally available maps, maps available from external providers, PNT availability maps, and so forth. Further inputs can include congestion levels according to time of day, landmark information, weather conditions, or any other static or dynamic data source relevant to informing the user according to novel requirements derived in future research.

Following strategic planning, the user begins their journey where real-time detection and trajectory generation become the primary processes, allowing for the user to conduct each subtask and task according to the two fundamental requirements of obstacle and hazard awareness, and orientation and wayfinding ('Where am I?'). Strategic planning remains an active process in real-time detection, especially when moving between tasks, and the system

continues to poll and filter the data sets that are available to it, such as transport data, with a primary aim of determining the state of the network. In the event of changes in state, the alarm will trigger to notify the user of any journey changes, such as train platform alterations, and planning becomes the primary process to determine the revised onward journey.

Positioning, localisation and mapping, and environment detection also facilitate real-time detection. Any failure in these processes, determined by a pre-set or actively calculated tolerance according to the user's requirements, will trigger an alarm. Such events can include, but are not limited to, poor PNT availability or a device component failure. Similarly, behavioural planning to facilitate trajectory generation will be strongly associated with the user requirements and the environment in which they operate in, leveraging empirical models derived through experimentation, as was detailed in Chapter 5. Failures to reliably generate trajectories within tolerances would also trigger an alarm. Throughout the entire system function, device-user and device-device communication remains an active process, as per the critical user requirement of delivering information to the user as the user requests it (system interrogation and ICOP).

8.2.2. Positioning and Localization Function

A novel proposal from the user requirements is that a task or subtask is not constrained to occurring in either an outdoor or indoor environment. Rather, the task or subtask correlates to the user's motivation within a catchment area which can include outdoor and indoor environments, and a transition between them. Figure 8.2 introduces the realistic operational scenario of the user entering the Skempton Building at Imperial College London. The main task is therefore to enter the building with subtasks including navigating the walkway to the building (outdoor), locating the entry point (outdoor), utilising the entry point (transition), and then navigating within the building (indoor). Indeed, the task involves outdoor, indoor, and transition phases, and the functional system architecture must make provisions for each to satisfy the complete user journey.

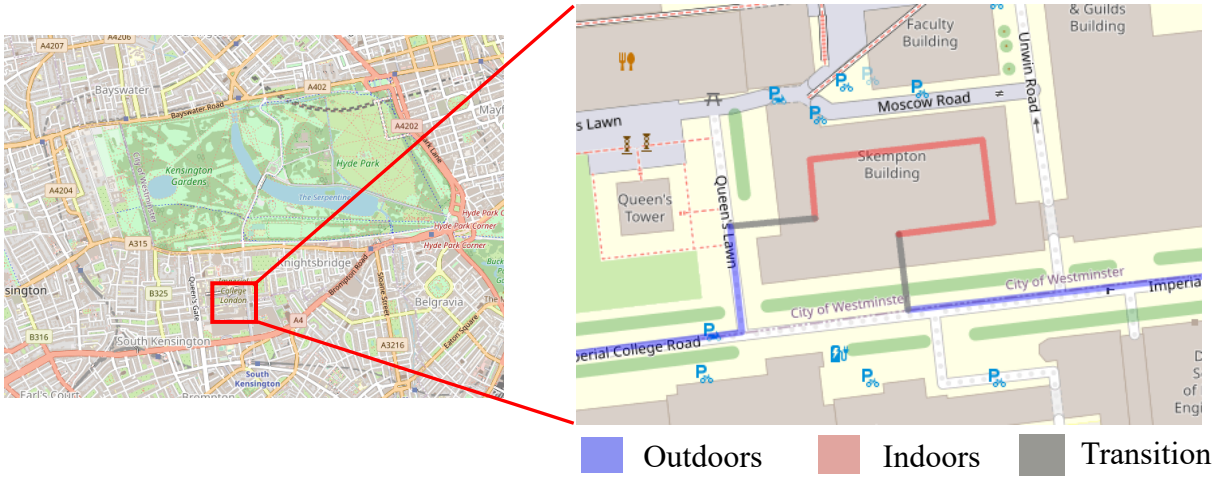


Figure 8.2: Realistic operational scenario in which the user enters the Skempton Building at Imperial College London.

Alghananim et al. (2022) therefore proposed the methods of delivering the complete system's positioning and localisation function in Figure 8.3. The three candidate PNT technologies

selected were Global Navigation Satellite Systems (GNSS), Inertial Measurement Unit (IMU), and Bluetooth positioning. These were chosen following an extensive PNT technology review conducted during WP2 within the project to determine their failure modes and feasibility of mitigation. Moreover, the positioning hardware within the current WeWALK version during the project only allowed for these methods of positioning.

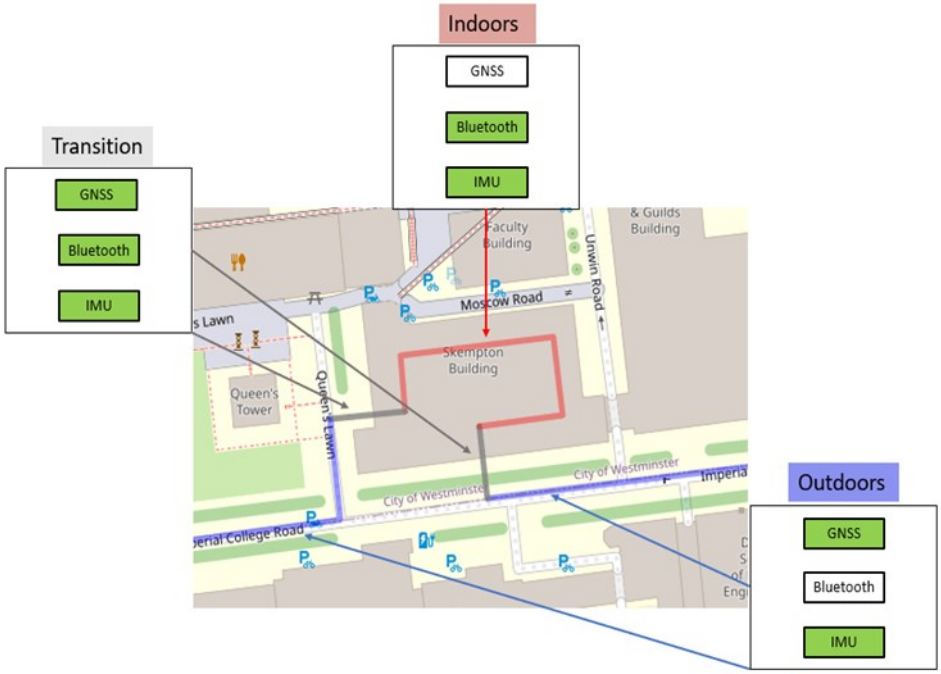


Figure 8.3: Positioning and localisation function for entering the Skempton Building at Imperial College London.

GNSS is widely used for outdoor positioning given its good global coverage, although it is limited in that it typically cannot provide coverage in indoor spaces resulting from signal attenuation and blockage. Moreover, outdoor positioning with GNSS can be compromised by dense urban areas where GNSS signal blockage and multipath result in unavailability and measurement error, respectively. Bluetooth-powered systems where the user's device connects to Bluetooth beacons positioned around an indoor space are therefore typically employed in indoor positioning applications; however, Bluetooth systems remain susceptible to blockage and multipath.

Therefore, regardless of outdoor or indoor application, GNSS and Bluetooth signals may be compromised, and integration with IMU positioning techniques is proposed to supplement the positioning solution. This is as IMU provides a relative positioning system allowing for continuity during outages of the absolute positioning system provided by GNSS and Bluetooth. However, as the instantaneous position from a relative positioning system depends on the position calculated immediately before it, the position is susceptible to drift over time. Absolute and relative positioning systems are therefore considered to be complementary, and the indoor positioning function of this project therefore leverages both Bluetooth and IMU positioning.

8.2.3. Indoor Positioning Function

Alghananim et al. (2022) developed the mathematical models underpinning the indoor positioning function. These are novel and were developed according to the constraints of the

user requirements and functional system architecture. However, they are outside of the scope of this thesis, and are described to contextualise the advancements and limitations of the system in user testing (which is contributed by this thesis). The indoor positioning function is comprised of 5 stages that integrate Bluetooth and IMU positioning with an integrity layer. The specific positioning techniques facilitated by Bluetooth and IMU are Bluetooth Angle Of Arrival (AOA) and IMU dead reckoning, and are integrated as follows:

1. Bluetooth mesh configuration (C): Defines the position, orientation, and distribution of the Bluetooth anchors, a novel development in Bluetooth positioning.
2. Bluetooth positioning (BL): Outputs the design and observation matrix (inputs for IMU and BL integration) and computes the BL-only solution.
3. IMU positioning (IMU): Outputs estimated heading angle and travel distance (inputs for IMU and BL integration) and computes the IMU-only solution.
4. IMU and BL integration (EKF): Integrates the output data from stage 2 and 3 using an Extended Kalman Filter (EKF).
5. Integrity layer (INT): Computes the protection level (a best estimate of the actual position error) needed to warn the user for when the system is not performing within acceptable tolerances.

Appendix O presents a visual representation of this architecture. The integrity layer described in stage 5 is of particular importance as it is a measure of trust in the positioning solution. This is intended to vary according to the mission criticality of the user's motivation and operational environment. Laboratory testing by Alghananim et al. (2022) suggests a maximum protection level of 2 metres using the integrated IMU and BL position. This falls below the typical 6 ± 1 m alert distance for platforms, escalators, and other specific features defined by Wayfindr (2018).

8.2.4. Sub-architectures of the Indoor Positioning Function

8.2.4.1. Bluetooth Mesh Configuration and Positioning

The Bluetooth positioning system delivered by Alghananim et al. (2022) is sensitive to anchor and initial tag positioning, requiring a critical calibration process. Eight anchors are recommended for spaces of size 60 to 110 m^2, positioned according to Figure 8.4 (Alghananim et al., 2015). Between five and ten tags are required for the calibration of each anchor. These should be distributed horizontally (spaced 3 to 10 m apart), at different elevations, with good geometry, and at a maximum of 40 degrees from the line of sight. Finally, the tags must also remain static for 30 to 60 seconds.

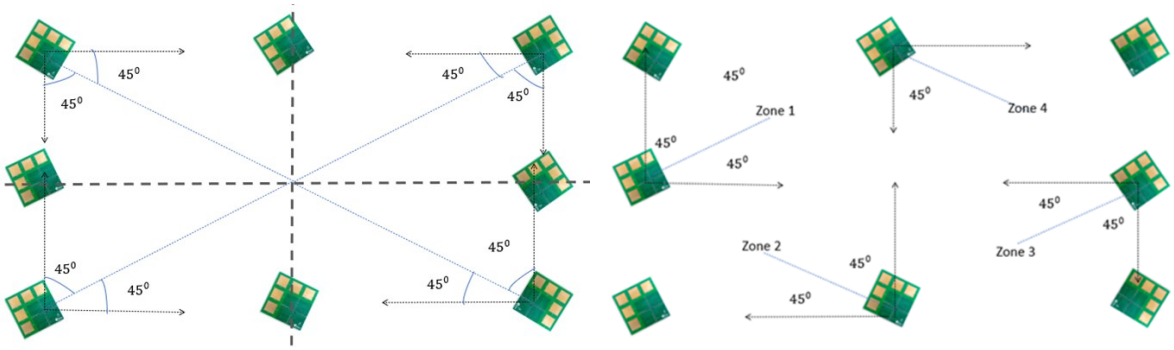


Figure 8.4: Recommended anchor positions in a rectangular room by Alghananim et al. (2022).

The calibration process, while novel and important in the delivery of enhanced system reliability, introduces usability constraints; real-world environments with varying geometries and dynamic elements will require complex anchor positioning. Moreover, the tag initialisation time requiring minimal movement may not be feasible in an active mobility scenario. As such, these constraints will be noted and further explored in system testing with visually impaired participants.

8.2.4.2. IMU Positioning

The IMU dead reckoning solution requires several variable inputs. This is particularly important as a reliable positioning output is dependent on the effective prediction of human behaviour. Several variables have therefore been introduced following the user requirements review, and these are detailed in Table 8.1 as follows (Alghananim et al., 2022).

Variable	Value	Unit	Explanation
g	9.80665	m/s^2	Gravity value
K_s	0.41		Coefficient used to estimate step length, estimated value for cane swing behaviour
K_h	0.45		Coefficient used to estimate step length, estimated value for holding still behaviour
β_{imu}	0.033		Coefficient used to estimate heading angle from gyroscope and accelerometer
β_{marg}	0.041		Coefficient used to estimate heading angle from gyroscope, accelerometer and magnetometer
B_{ref}	48.9	μT	Magnetic field reference at ICL acquired from https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm
B_{bound}	10	μT	Used with ref to detect soft iron disturbance and determine whether magnetometer measurements are used for heading computation
f_{imu}	50	Hz	Sampling frequency of raw IMU measurements
$f_{walking}$	2	Hz	Threshold for VIP walking frequency based on assumption
$f_{cut-off}$	0.08	Hz	Cut-off frequency of the Butterworth low pass filter, determined as $2 \times f_{walking} \div f_{imu}$
θ_d	25		Distance between adjacent peaks/valleys in yaw angle
θ_p	20	degree	Prominence to determine peak/valley in yaw angle
a_d	25		Distance between adjacent peaks/valleys in acceleration norm
a_p	0.5	m/s^2	Prominence to determine peak/valley in acceleration norm
Th_{angle}	100	degree	Threshold of angle change to solve jumping issue near $-\pi$ and π

Table 8.1: Variables input for IMU dead reckoning positioning by Alghananim et al. (2022).

The sample values listed in Table 8.1 were used for preliminary system testing in the Skempton Building and are included for indicative purposes only. The system can accept modifications of these values as the understanding of the user's behaviour is developed. The step length

coefficients K_s and K_h are estimated in a calibration phase where the user walks a 5-metre straight path. The thresholds $f_{walking}$, θ_d, θ_p, a_d, a_p, and Th_{angle} are determined according to the user's walking behaviour. Other coefficients are dependent on the system's specific environment and not the visually impaired user's walking behaviour. As such, they are not investigated in further experimentation.

The IMU positioning system's dependence on walking behaviour necessitates behavioural studies in different environments in which its use is intended. This could include input variables for when the user is operating individually, in crowds, with the use of other mobility aids, and in familiar and unfamiliar environments. Such additional variables should be considered as 'features' of the system, allowing adaptation to the varying operational scenarios discussed within this thesis.

Indeed, the input variables for walking behaviour are continually being expanded to include data obtained from the crowd dynamics experiments detailed in Chapter 5. An output of this extended analysis is incorporated within the version of the positioning system utilised throughout the project duration. This is the novel incorporation of cane behaviour within the IMU dead reckoning solution to create one that is specific to the visually impaired user. The technique is named Visually Impaired Pedestrian Dead Reckoning (VIPDR) (Appendix O).

In step detection and when the cane is held still, the periodic feature of accelerometer measurements prevails. The peaks and troughs of vertical acceleration allows for a typical pedestrian dead reckoning approach to be used. During detected cane swings, a high correlation is assumed between steps and swings following the review of experimental data in Chapter 5, and step detection therefore becomes reliant on detecting swing behaviour (yaw angle). A limitation of this implementation is that the calibration process is static. Further development of the system aims to dynamically vary these coefficients according to the user's changing behaviour.

8.2.4.3. Positioning Integration and Integrity Layer

The position solutions generated from Bluetooth and IMU are fused through an Extended Kalman Filter (EKF). The integrity layer proceeds and establishes the protection level, a critical system output configured for the user requirement of measurable trust in the navigation system (Elhajj & Feghali, 2020). As the protection level is the best estimate of the actual positioning error, it can be combined with an alert limit (according to the operating environment) for when the system is performing below requirements and should therefore not be used. Alghananim et al. (2022) suggests a 2-metre protection level according to the specific Bluetooth and IMU-based indoor positioning function utilised throughout this project.

8.3. Preliminary System Testing and Iteration

8.3.1. Experimental Methodology

Two separate experiments were designed and executed throughout the project duration:

1. A preliminary experiment that investigated the system's basic functionality and any critical errors (without participant recruitment). This experiment occurred in the fourth quarter of 2021.

2. An experiment that recruited participants with and without visual impairments to discover different walking behaviours and the system's ability to capture them. This experiment occurred in the first quarter of 2022 with ongoing analysis extending beyond the project end date of 31st March 2022. Only VIPDR's operation is investigated in this thesis given its primary dependence on the user's behaviour. Contrastingly, BL positioning is not primarily dependant on user behaviour, and is therefore outside of the scope of this thesis.

The preliminary experiment was conducted within the Design Studio at the Skempton Building at Imperial College London by Alghananim et al. (2022). Figure 8.5 illustrates the waypoints, ground truth path, anchor positions, and the start position within this environment. The ground truth path was visually displayed using reflective tape and all positions were measured using a total station.

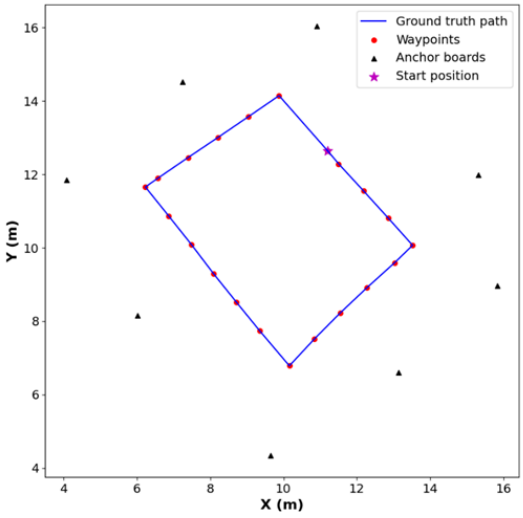


Figure 8.5: Waypoints, ground truth path, anchor positions, and the start position for preliminary experiment.

The test commenced with a researcher from the project team holding a cane with IMU tag attached (Figure 8.6), standing at the starting point for 10 seconds following the start of data collection for initial calibration, and then traversing the path at normal walking speed. Tests with and without cane swing were conducted. Bluetooth AOA data was collected from all eight Bluetooth anchors through serial port connections to three laptops, and IMU data was downloaded wirelessly through Wi-Fi connectivity.

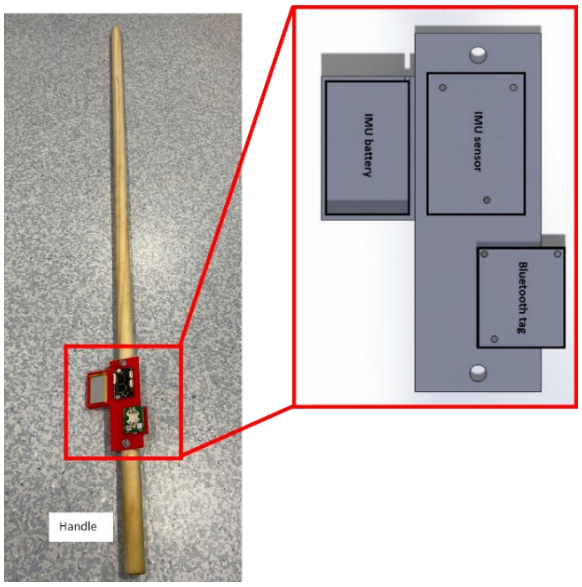


Figure 8.6: Cane and tog mounting used in preliminary experiment.

The cane utilised in preliminary testing, as shown in Figure 8.6, was approximately the same length as the WeWALK smart cane supplied (54 inches), and was used to facilitate drilling of the tag mounting bracket for precise positioning. This would not have been possible with the graphite shaft of the WeWALK smart cane, although a WeWALK smart cane was utilised in the second experiment to ensure realistic visually impaired operation, at the potential risk of reduced positioning consistency.

8.3.2. Results and Fundamental Analysis

Figure 8.7 visually summarises the findings from the preliminary experimentation. Preliminary testing evidences the effective integration of Bluetooth AOA and IMU DR in reducing positioning error in simple experimentation; jitter, increased error in close proximity to the anchors, and position drift were reduced, although errors in closer proximity to anchors prevailed. The integrity layer was always available and provided a maximum level of protection below 2 m.

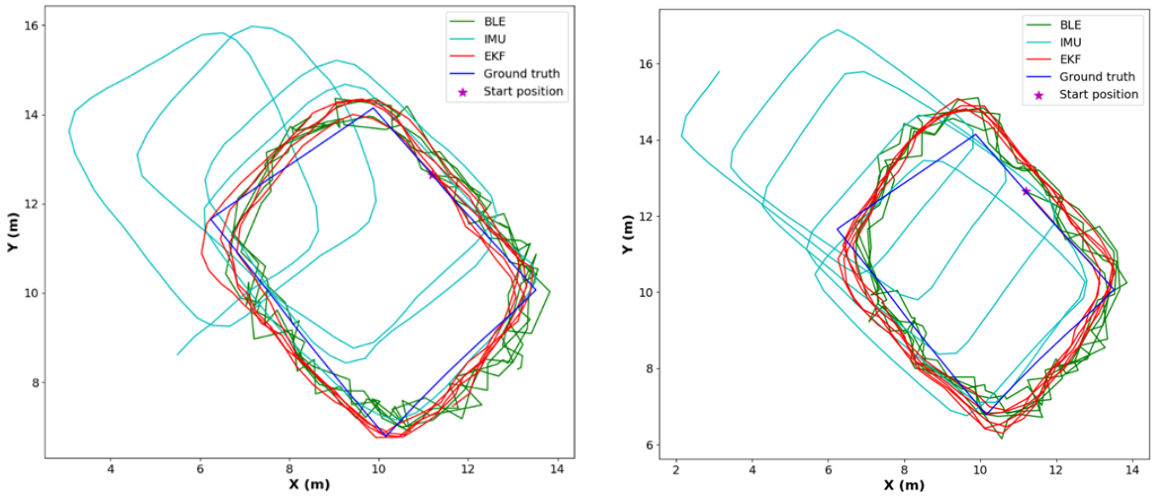


Figure 8.7: Overview of positioning solutions with (left) and without (right) cane swings in preliminary experiment (Alghananim et al., 2022).

Of particular interest is the IMU positioning. The solution without cane swings presents a visually more accurate representation of the ground truth relative to the solution with cane swings, and this was found by Alghananim et al. (2022) to be a result of the more stable heading angle recorded when the cane was held still. Given variations in cane usage, the assessment of vertical acceleration and heading is necessitated in experimentation with visually impaired participants.

While the positioning system could have been depended on in this instance, the preliminary experimental methodology was unrepresentative of realistic use. Eight anchors with optimal positioning were utilised. Furthermore, the sighted participant traversed a simple rectangular ground-truth path with uniform speed, cane movement, and walking character. It is unlikely that the visually impaired user will behave similarly, especially given orientation errors and their subsequent impedance on walking behaviour. Further experimentation was therefore necessary to qualify the effectiveness of these positioning methods on visually impaired users.

8.4. Experiment with Participants

8.4.1. Experimental Methodology

Following the preliminary experiment by Alghananim et al. (2022), an experiment was conducted throughout the first quarter of 2022, and included mobility testing and surveys of participants with and without a visual impairment. The experiment had two primary aims:

1. Through mobility testing, identify a range of walking factors affecting visually impaired people when moving in a simple indoor space, and the effectiveness of VIPDR in capturing these. Factors include walking speed, visual function, perceptions towards the experiment, and cane usage.
2. Through user surveys, identify and quantify the challenges associated with visually impaired mobility in a range of indoor and outdoor environments, (discussed in Chapter 9).

It was hypothesised that each visually impaired person will demonstrate very different walking behaviours given their own physiological and psychological ability, as supported by conclusions from the crowd dynamics experiment detailed in Chapter 5. Furthermore, these were expected to correlate with the magnitude of mobility problems arising in realistic environments. In quantifying VIPDR's effectiveness in this experimentation, system iteration would be better informed to meet the user requirements derived through this thesis.

The mobility walk course erected for the experiment was located in room 064 of the Skempton Building at Imperial College London. This comprised a walking path with 8 nodes where 4 nodes (A, B, C, D) were positioned in a rectangular walking perimeter path of dimensions 8 m by 5 m. The remaining 4 nodes were positioned as a smaller rectangle (E1, E2, E3, E4) within the outer rectangle with diagonal walking paths extending to each corresponding corner node pair. 7 Bluetooth anchors (BL1, BL2, BL3, BL4, BL5, BL6, BL7) were positioned around the room. Figure 8.8 draws the coordinate grid (in metres) that denotes the walking path layout and anchor positions.

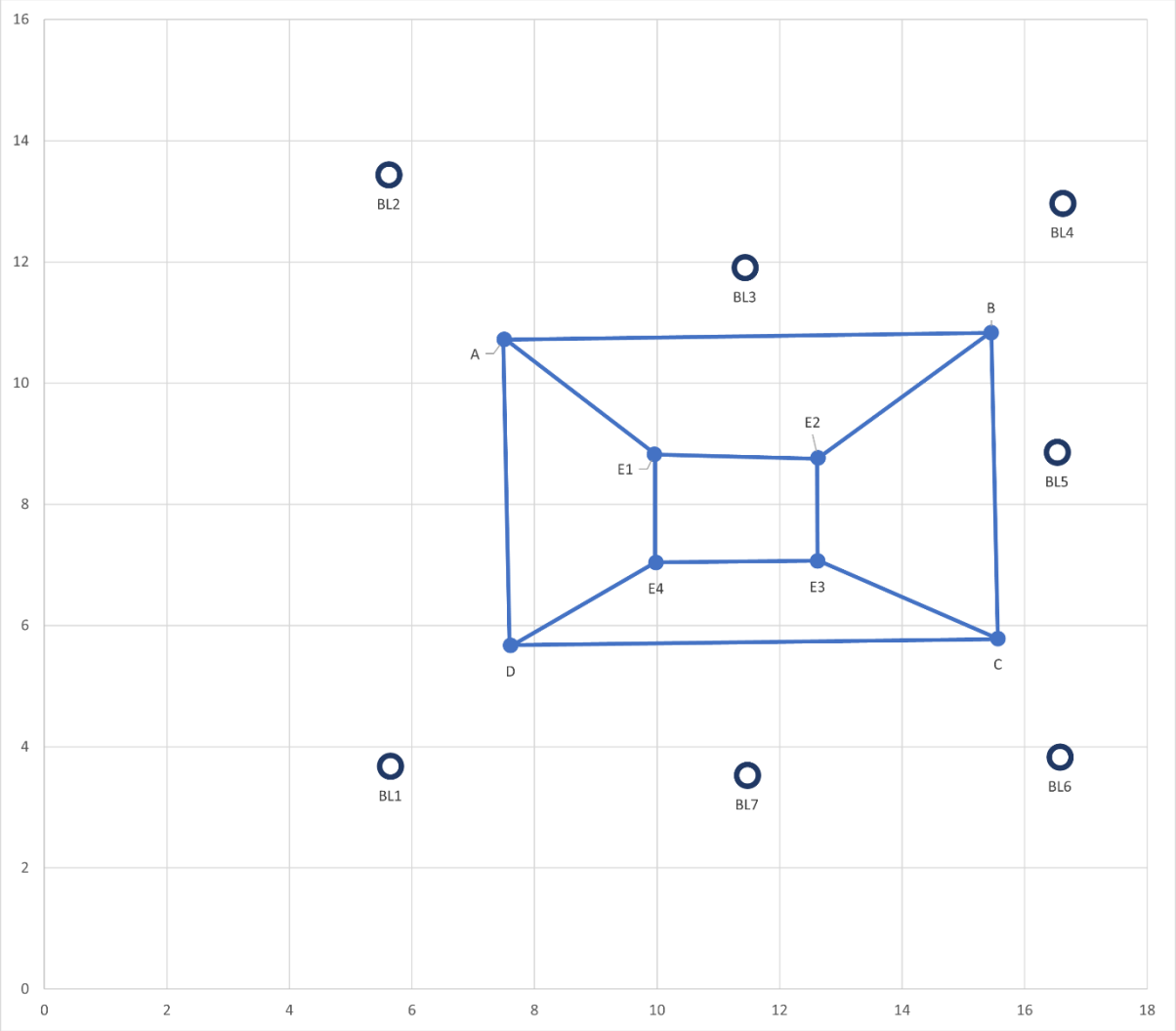


Figure 8.8: Waypoints, ground truth path, anchor positions, and the start position for preliminary experiment.

The walking path distances between each node pair are displayed in Table 8.3 and the positions of the nodes and anchors were measured using a total station. The inner rectangular walking path (E1, E2, E3, E4) encompassed a floor to ceiling column and this was utilised as a boundary to halt the participant as they traversed from the outer to the inner nodes. The experiment procedure was as follows:

1. The participant was positioned at A, facing B, and instructed to wait for 10 seconds while the system began recording and calibration.
2. The participant was then verbally instructed to walk at a comfortable speed to B, and told to stop when they arrived.
3. This was repeated for movement from B to C, C to D, D to A, A to E1, E2 to B, B to E2, E3 to C, C to E3, E4 to D, D to E4, E1 to A, A to D, D to C, C to B, and B to A.

Each participant therefore completed two passes of each node pair (one forward and one backward), and this was intended to provide additional data points as well as to determine any changes in walking behaviour over time as the participant's familiarity with the environment increased. Passes across the edges of the inner rectangle were not measured given their short distance (such as E1 to E2, E2 to E3, and so forth). Only light physical touches were used to

guide the walking participant back to the walking path if significant deviation thought to affect safety was observed.

To control participants' knowledge (familiarity with the course), the shape of the course and experimental instructions were verbally delivered prior to the start of the experiment. Participants were also asked to confirm that these instructions were well-understood. The walking path distances between each node pair are displayed in Table 8.2. Henceforth, each node pair is referenced as a 'section' of the walking path.

Section	Distance (m)
A-B	8.0
B-C	5.0
C-D	8.0
D-A	5.0
A-E1	3.1
E2-B	4.0
B-E2	4.0
E3-C	3.2
C-E3	3.2
E4-D	2.7
D-E4	2.7
E1-A	3.1
A-D	5.0
D-C	8.0
C-B	5.0
B-A	8.0

Table 8.2: Walking path distances between each node pair.

The walking path for each section was marked using tape with a high contrast to the carpeted floor, as shown in photographs of the mobility course in Figure 8.9. The intention was to create an explicit visual reference point for participants with varied visual function. Need for structural elements, additional lighting, or orientation methods requiring processing beyond visual function is reduced. Illumination was sufficiently controlled across the walking path given that the room, located at basement-level, was predominantly illuminated by artificial, controllable lighting. Illumination was measured at each section's midpoint, and was found to vary from 80 to 130 lux with an average of 110 lux across the walking surface.



Figure 8.9: Photographs of the mobility course.

The position of the mobility course and the layout of the room were hypothesised to be more challenging for the positioning system than in the preliminary experiments. The walking path design was therefore intentional in exploiting these challenges to discover the system's vulnerabilities. Firstly, the location of the room at basement-level restricted the use of any auxillary positioning systems (such as GNSS) beyond that of the indoor positioning system. Moreover, the position of the central pillar encompassed by the inner rectangular walking path caused Non-Line of Sight (NLOS) between certain anchors and the user as they traversed between the outer and inner rectangle. Furthermore, only 7 anchors were used, one less than the 8 recommended by Alghananim et al. (2022) for a walking area of these dimensions. This can be observed in Figure 8.12 where an additional anchor should have ideally existed between BL1 and BL2. Finally, the positioning of BL3 and BL5 at the midpoints of paths A-B and B-C, respectively, were closer to the walking path than recommended.

A single IMU tag was active throughout each participant's traversal of the mobility course. Figure 8.10 illustrates the two methods of tag attachment to the participant, dependant on cane use, as follows:

1. NSPs and VIPs that did not use a cane: Participants wore a light helmet with the tag attached atop it.
2. VIPs that did use a cane: Participants used a WeWALK cane with the tag affixed to the cane's shaft.



Figure 8.10: Tag attachment to helmet (left) and cane (right) according to the participant's cane use.

Following mobility testing, each participant completed a verbally administered questionnaire that aimed to determine cause of visual impairment and impact on visual function (if applicable), the participant's confidence in mobilising through different indoor and outdoor spaces, and their sentiment towards the experiment. As with the crowd dynamics experiment detailed in Chapter 5, visual function testing using standard clinical measures was not conducted given timing constraints, although a good understanding of the participant's useful vision was attained through self-report.

This questionnaire is a critical part of this experimentation; according to the prior literature review, the derivation of visually impaired user requirements from a cross-environmental study with the same study group has not yet been conducted. While the sample size within this

experiment is not sufficient for statistical significance, the breadth of visual impairment included is expected to introduce distinctions in the challenges and coping mechanisms undergone by each participant. The methodology and results from this cross-environmental study are detailed in Chapter 9.

8.4.2. Overview of Participants

The experiment involved the recruitment of 10 participants with and 5 participants without a visual impairment, with the participants without a visual impairment acting as a control group and undergoing an identical experimental protocol. People with any cognitive or mobility impairments, or any other disabilities apart from a visual impairment, were excluded from the study. Similar recruitment methods to the crowd dynamics experiment detailed in Chapter 5 were used, including through email, social media communication, and visually impaired stakeholder organisations to ensure a broad selection process.

Moreover, participants that had taken part in the previous experiment were also invited to participate given this thesis' finding that visually impaired mobility testing should prefer long-term data collection on a single participant rather than short-term data collection on several participants (where only one approach is possible). As a result, 8 of the 10 visually impaired people that participated in this experiment had previously participated in the prior experiment conducted within this thesis. Table 8.3 overviews the visually impaired participants involved in this experiment, their identifier in the prior experiment (where applicable), age, gender, impairment, vision loss category, and mobility aids typically used in daily activity. Vision loss was categorised as Blind (B), Central Vision Loss (CVL), and Peripheral Vision Loss (PVL) according to recommendations within the user requirements.

ID	Ex -ID	Age (Years)	Gender	Impairment	Vis. Loss	Aids
V1	C2	63	F	Retinitis Pigmentosa	B	Long Cane
V2	A2	67	M	Still's Disease	B	Guide Dog
V3	-	19	M	Leber Congenital Amaurosis	PVL	Symbol Cane
V4	A1	57	M	Glaucoma, Retinal Detachment	PVL	Magnifier
V5	G1	62	M	Glaucoma	B	Long Cane
V6	D1	54	M	Congenital Hereditary Endothelial Dystrophy	CVL	Long Cane
V7	-	55	M	Retinitis Pigmentosa	CVL	Long Cane
V8	E1	55	M	Retinitis Pigmentosa	B	Long Cane
V9	E2	62	F	Glaucoma, Detached Retina, Macular Hole	CVL	Long Cane, Monocular
V10	H1	59	F	Stargardt's Disease	CVL	Long Cane, Magnifier

Table 8.3: Overview of visually impaired participants.

Visual function metrics were collected according to the participant's visual impairment classification in their CVI, namely Sight Impaired (SI) or Severely Sight Impaired (SSI), and self-reported visual acuity (VA), contrast sensitivity (CS), and visual field (VF) according to how useful the participant finds each function in daily activity. Table 8.4 summarises these findings. An improvement from the crowd dynamics experiment conducted previously is that a 5-point Likert scale was used across the entirety of the questionnaire including self-reported

visual function (replacing the 3-point scale used previously for VA, CS, and VF). Here, 1 represented 'very poor', 3 represented 'neutral', and 5 represented 'very good'.

ID	CVI	Vis. Loss	Impairment	VA	CS	VF	Avg.
V1	SSI	B	Retinitis Pigmentosa	1	1	1	1.0
V2	SSI	B	Still's Disease	1	1	1	1.0
V3	SSI	PVL	Leber Congenital Amaurosis	3	4	2	3.0
V4	SI	PVL	Glaucoma, Retinal Detachment	3	3	3	3.0
V5	SSI	B	Glaucoma	1	1	1	1.0
V6	SSI	CVL	Congenital Hereditary Endothelial Dystrophy	2	2	2	2.0
V7	SSI	CVL	Retinitis Pigmentosa	1	2	3	2.0
V8	SSI	B	Retinitis Pigmentosa	1	2	1	1.3
V9	SI	CVL	Glaucoma, Retinal Detachment, Macular Hole	2	2	3	2.3
V10	SSI	CVL	Stargardt Disease	2	2	4	2.7
Avg.				1.7	2.0	2.1	1.9
SD				0.8	0.9	1.1	1.0
CV				48.4	47.1	52.4	49.3

Table 8.4: Overview of visually impaired participants' visual impairment.

Each participant was also asked to describe their vision and their methods of overcoming the barriers that their impairment poses. There exist visible correlations between severity of visual impairment (according to CVI and B/CVL/PVL classification) and the self-reported measures of visual function. For instance, the four participants registered as SSI and B reported the four lowest average scores of visual function. Only participant V8 reported a minimal ability to detect contrast (scoring 2 out of 5). Similarly, participants with PVL reported better VA and CS than participants with CVL, while participants with CVL reported a slightly better VF than those with PVL. However, the correlation between VF and those with CVL or PVL remains weak given each participant's relative understanding of their visual field and whether this relates to the central or peripheral field. Clinical visual field assessments would therefore have been beneficial here.

The spread of visual impairment and visual function was also satisfactory given the small sample size, with SI and SSI participants representing each of B, CVL, and PVL, although two further participants with PVL would have benefited the balance between each categorisation. Additionally, a range of congenital and acquired visual impairments were observed including, but not limited to, those affecting the retina, optic nerve, cornea, and macula. As a result, the range of reported visual function was broad, and this was reflected by an average coefficient of variation of 49.3% when considering the average scores of VA, CS, and PV. An overview of participants without a visual impairment is presented in Table 8.5.

ID	Age (Years)	Gender
N1	18	M
N2	23	F
N3	25	M
N4	61	M
N5	36	F

Table 8.5: Overview of participants without a visual impairment.

In like manner to the prior crowd dynamics experiment, more male (7) than female (3) visually impaired participants took part in this study. Discrepancies in the ages of participants with and without a visual impaired were also present, as described in Table 8.6 where the average age, its standard deviation, and coefficient of variation for Visually Impaired Participants (VIP) and Normally Sighted Participants (NSP) are calculated. The B group were the oldest, on average, followed by the CVL group (presenting the smallest deviation in ages), and the PVL group, which only included two, rather than four, participants.

Group	Age (Years)		
	Avg.	SD	CV (%)
B	61.8	5.0	8.1
CVL	57.5	3.7	6.4
PVL	38.0	26.9	70.7
VIP	55.3	13.4	24.3
NSP	32.6	17.2	52.7

Table 8.6: Participant age analysis.

This is an acceptable distribution given that VIPs presented congenital and age-related impairments that degrade with time. For instance, two participants in the B and CVL group had RP, although the disease had progressed further in the older B participant, leaving them without usable sight. The limitation of this study was the younger average age of the NSPs (32.6 years) relative to VIPs (55.3 years), although a larger variation of ages was present in NSPs (CV of 52.7% versus CV of 24.3% for VIPs). However, the nature of visual impairment is hypothesised to prevail over age given the strict exclusion criteria of any other age-related impairments throughout recruitment.

8.5. Assessing Walking Behaviours and VIPDR – Results and Discussion

8.5.1. Walking Behaviours of VIPs and NSPs (System Input)

Appendix P presents the time required for each VIP and NSP to traverse each section of the walking path. To extend data collection and evaluate the effect of familiarity, certain participants completed several passes of the experiment. These are denoted by 'PX' following the participant ID where X is the pass number. The time to traverse each section for each participant is derived through observing the video footage captured from the experiment. The start and end time is defined when the 'start' and 'stop' command is heard, respectively. To check consistency, the departure and arrival of the participant is visually confirmed at each node. Effective speed is the shortest section length divided by the time required to traverse this section. Figure 8.11 graphs the effective speed of VIPs and NSPs, considering the total distance of all sections divided by the time required to traverse them.

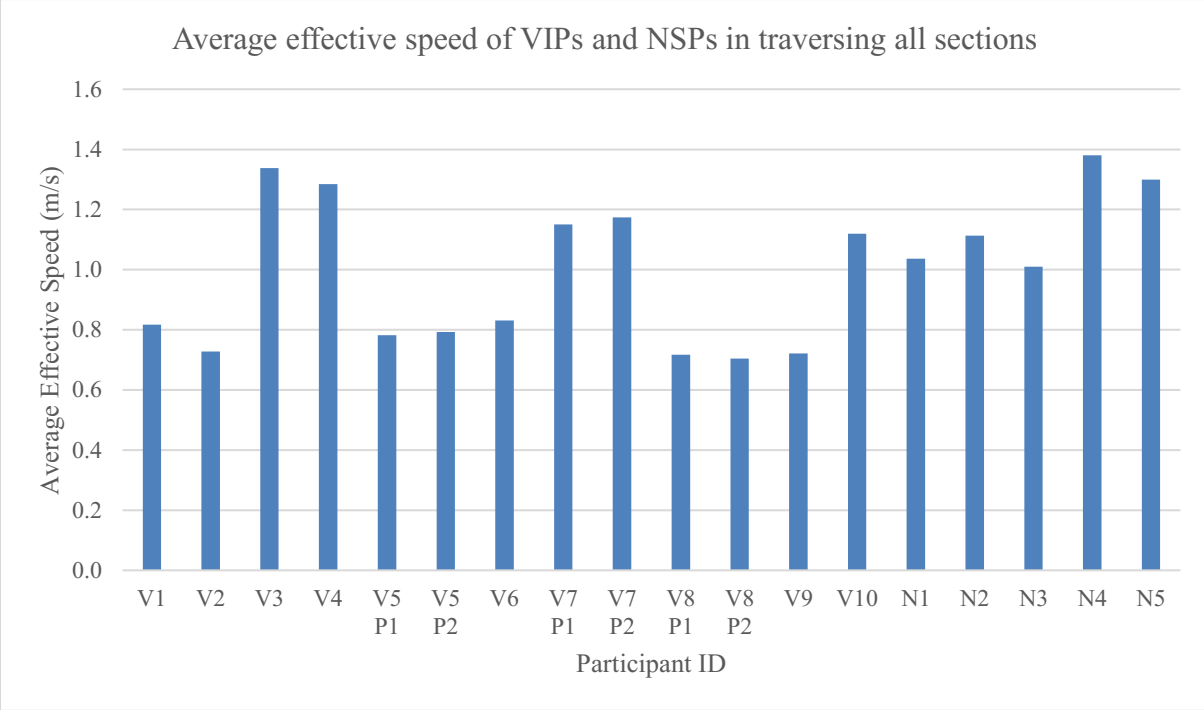


Figure 8.11: Average effective speed of VIPs and NSPs in traversing all sections.

Only the first pass, where applicable, is used to calculate the VIP and NSP group average effective speed. The VIPs and NSPs presented group average effective speeds of 0.9 m/s (SD = 0.2 m/s, CV = 26.0%) and 1.2 m/s (SD = 0.2 m/s, CV = 14.0%), respectively. As expected, NSPs presented an increased overall effective walking speed, both in magnitude and consistency, relative to the VIPs. The repeated pass increased performance for V5 and V7 but did the contrary for V8. However, all performance changes within repeated passes were insignificant and within margin of error (V5, V7, and V8's average effective speeds remained at 0.8 m/s, 1.2 m/s, and 0.7 m/s, respectively).

The experiments conducted in Chapter 5 presented a different outcome where repeated passes constituted a consistent and significant performance increase. This discrepancy is attributed to the simpler walking environment in this experimentation, particularly in the exclusion of obstacles. It can therefore be concluded that familiarity within this environment was controlled, and that this did not significantly hinder the performance of the observed participants.

Notably, V3 and V4 (PVL) yielded effective walking speeds above all other VIPs and the NSP average. The five lowest walking speeds were recorded for all B participants (registered SSI), and one CVL participant (V9, registered SI). The inclusion of V9 was surprising given that they had better visual function (both in self-report and CVI classification), than the B group. Figure 8.12 plots average effective VIP speed against average self-reported visual function. This is to understand if user input of visual function may assist the system in anticipating their range of effective speed.

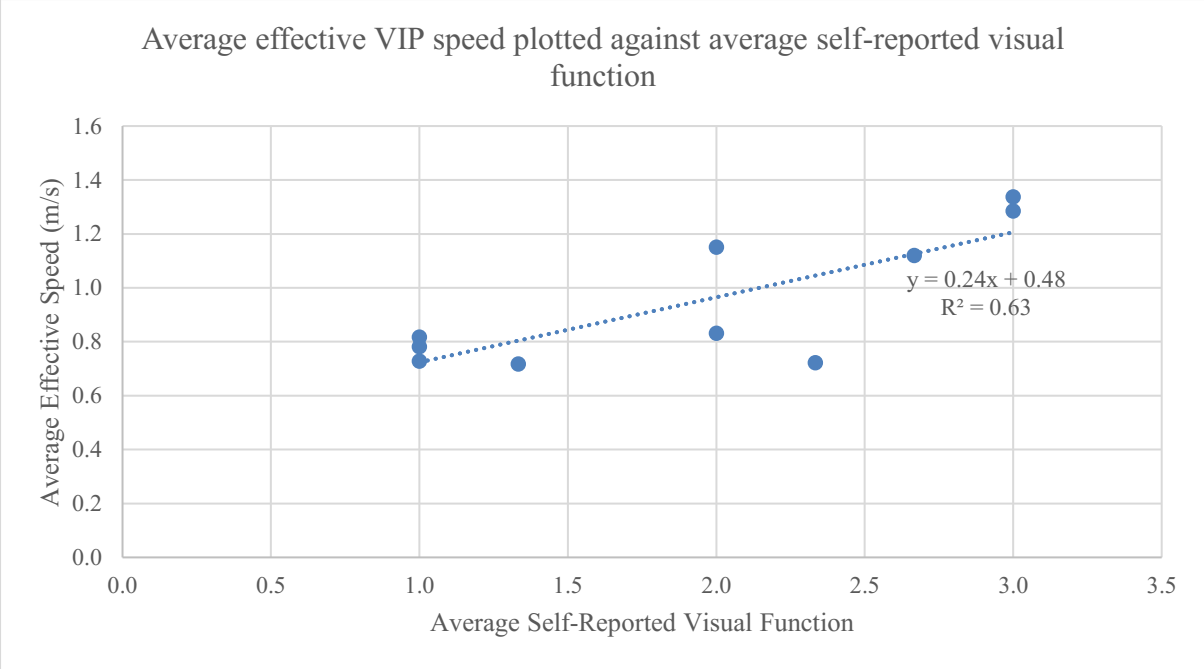


Figure 8.12: Average effective VIP speed plotted against average self-reported visual function.

Indeed, according to the R^2 value of 0.63, there appears a moderate correlation between effective speed and self-reported visual function. Figure 8.13 presents the Coefficient of Variation (CV) of effective speed across the total walking path for each VIP. An R^2 value of 0.01 suggests no correlation between self-reported visual function and consistency of effective speed between each section of the walking path. However, all CVs fall below 20%, and represent Standard Deviations (SD) between 0.1 and 0.2 m/s across all sections. The VIPs are therefore very consistent in their effective speed within the entire walking path. In this instance, a user input of visual function to estimate effective speed would have been feasible.

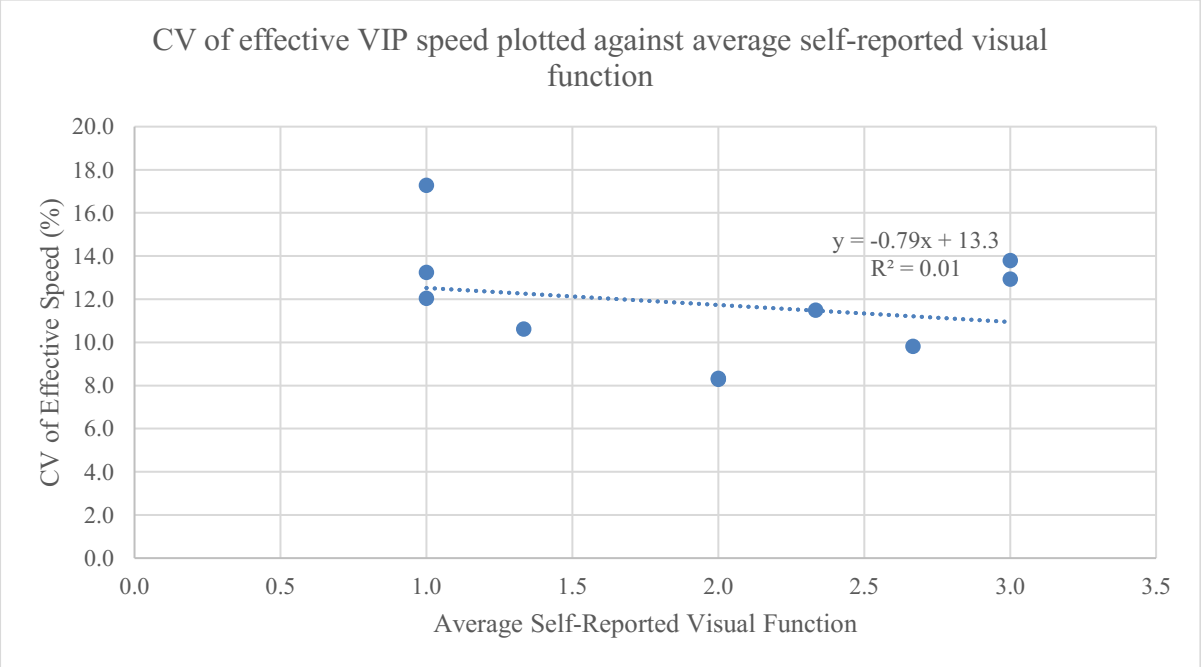


Figure 8.13: CV of effective VIP speed plotted against average self-reported visual function.

The average effective speed, average SD, and average CV for other participant demographics are calculated in Table 8.7. This assesses the average consistency of effective speed across the walking path for these participant demographics. Each group was consistent in its walking speed across the environment, regardless of section; CV ranged from 8.6% to 13.9%, and the maximum SD was 0.2 m/s for the PVL group. These results are limited by the small sample size of each demographic and are not applicable beyond this experimentation.

Group	Average Effective Speed		
	Average Value (m/s)	Average SD (m/s)	Average CV (%)
VIP - Cane	0.9	0.1	10.4
VIP - No Cane	1.0	0.1	13.9
VIP - SI	1.0	0.1	12.2
VIP - SSI	0.9	0.1	11.7
VIP - B	0.8	0.1	13.3
VIP - PVL	1.3	0.2	13.4
VIP - CVL	1.0	0.1	9.5
VIP - All	0.9	0.1	11.8
NSP - All	1.2	0.1	8.6

Table 8.7: Average, SD, and CV for effective speed per section for different participant groups.

Notwithstanding this limitation, the consistency of effective speed in this instance is confirmed. This is utilised to assess VIPDR's replicability across each section of the walking path. Of particular benefit is that the cane and no cane VIP grouping presented similarly consistent performance at 0.9 m/s (average SD = 0.1 m/s, average CV = 10.4%) and 1.0 m/s (average SD = 0.1 m/s, average CV = 13.9%), respectively. The comparison of cane versus no cane behaviour therefore considers two participant groups with similar average performance.

Finally, the confidence of participants during the experiment is assessed to determine if this impacted their walking behaviour. Confidence (also referenced as comfort) has been shown to positively correlate with VIPs' effective speed when operating individually (Chapter 5). Participants were first asked to score if their confidence influences their walking behaviour, and to provide comments as to why. Table 8.8 collates these results for both VIPs and NSPs. The score (S) was a 5-point Likert scale with the following options:

1. No influence
2. Minor influence
3. Neutral
4. Moderate influence
5. Major influence

ID	S	Comments
V1	4	I walk slower when I am less confident, especially as my sight degraded.
V2	3	Sometimes take my time, even if I'm not confident.
V3	4	The more confident I am, the higher the chance that I will walk faster. In some areas, even if I am not confident, I trust myself and my sight enough to know that there is nothing in front of me.
V4	2	I tend to walk at my pace, and my sight doesn't really affect my pace, certainty in a confident environment. Even if I am not sure where I am going, I want to get to

		a point where I know I have done right or wrong. It's contextual, if I roam around a cluttered pub then I am sure that I will slow down.
V5	5	Completely correlated. I'm less confident in unknown places, and I don't want to hurt myself, so I slow down. I want to go faster but I also want to be safer.
V6	5	My confidence always affects my walking speed. When I am not confident, I walk slower, especially with roadworks, cycle lanes, and the new bollards being put in. If I follow tactile paving, it sometimes leads me into these obstacles and bollards, and that's very dangerous. It can be a minefield and it's sometimes easier and safer to take a bus to avoid roadworks and cycle lanes even when I could walk there, there's just too many crossings and things going on. If I know it's flat for the next mile, I will walk fast. When someone's guiding me and I trust them, I can walk fast and navigate many steps.
V7	4	It usually does. When I am not confident and need to make a mental map, I walk slower.
V8	4	My confidence is very important. I am a confident person but, in a new place, I'm not that confident. I would walk slower in a new place because I don't know what's around me. In a routine place where I have high confidence, I even get a bit lazy and don't use my cane properly, like using less cane swipes because I know where everything is. I have to put in much more effort in a new place.
V9	4	When I'm walking slower, I feel less likely to have an accident or fall. I always think more about tripping and falling, but I have heard of others who have received head injuries from above-ground obstacles.
V10	5	If I'm not confident, I will slow down. There is a danger, and I don't want to hurt myself, even though it feels good to walk at my natural speed, which is quite fast.
N1	2	A lot of the time, my walking speed depends on how urgent my schedule is. When it is to do with safety, I go faster.
N2	4	If I am walking in a hallway for the first time, I take my time to find which pathway I have to get out of. If I'm less confident, I walk slightly slower, especially if it's not a well-lit street, because my vision is worse at night and I don't want to trip on something.
N3	2	When less confident, I walk faster so that I can better understand my way around. I want to know it quickly. When I'm confident, I might also walk faster because I can, or walk slower because I know I can chill.
N4	5	If I don't feel confident, I go much slower. For instance, when carrying a big jug of water and not wanting to spill it, I walk slow. My mother got scared when she knew she physically couldn't walk very well, it correlates confidence with fear. If you have a fear of something, it holds you back.
N5	4	If I'm going somewhere and know exactly where I'm going, I would walk quick. If I'm less confident in where I was going then I would walk more slowly but, if I wasn't confident in my safety, then I would walk faster.

Table 8.8: Participants' ratings and comments on how their confidence affects walking behaviour.

The average VIP and NSP scores are 4.0 (SD = 0.9, CV = 23.6%) and 3.4 (SD = 1.3, CV = 39.5%). On average, VIPs attribute their confidence to have a greater effect on their walking behaviour than NSPs, although NSPs present a larger spread of results. This may be biased by the smaller size of the NSP group. 8 VIPs express that their confidence had either a moderate or major influence on their walking speed. These VIPs consistently described a slower walking speed as their confidence decreased.

V1 explains this to be a result of visual function degradation. 6 other VIPs (V5 to V10) correlate confidence with safety and familiarity, reducing their walking speed in areas where they are unfamiliar or feel unsafe. This sentiment pertains to trips, falls, collisions with obstacles, and forming a mental map. N2 and N4 correlate their confidence to similar factors, also walking more slowly in unfamiliar or hazardous scenarios. The remaining NSPs correlate confidence to other factors.

N1 finds their schedule to have greater effect on walking speed than their confidence. N3 explains that their walking speed increases as confidence decreases to discover an unfamiliar space more quickly. N5 correlates the reasoning for their reduced confidence to have contrasting impacts on walking speed; particularly, 'if I'm less confident in where I was going then I would walk more slowly but, if I wasn't confident in my safety, then I would walk faster.' In the sample observed in this experiment, it is concluded that higher self-reported confidence is likely to increase walking speed, particularly for the VIP group.

The confidence of participants when traversing the walking path was determined by self-report. Participants were asked to describe their confidence at:

1. The start of the experiment
2. When asked to walk in a straight line
3. When asked to make turns
4. The end of the experiment

A 5-pomt Likert scale was utilised with the following options:

1. Very poor
2. Poor
3. Fair
4. Good
5. Very good

Figure 8.14 presents the results of this exercise. The average self-reported confidence score across all VIPs and NSPs was 4.5 (SD = 0.8, CV = 17.0) and 4.9 (SD = 0.1, CV = 3.0), respectively. The NSPs reported a consistently higher confidence than VIPs throughout the experiment. However, the VIPs continued to report a high confidence overall, with 5 VIPs expressing full scores in all aspects. V5 expressed a slightly reduced confidence at the start of the experiment (scoring 3). The only participants with average scores below 4 were V1 (3.3) and V8 (3.5). These participants were both in the B group and reported a moderate influence of confidence on their walking behaviour. It can therefore be assumed that, with the exception of V1 and V8, the confidence of participants should not have limited their walking performance throughout this experimentation.

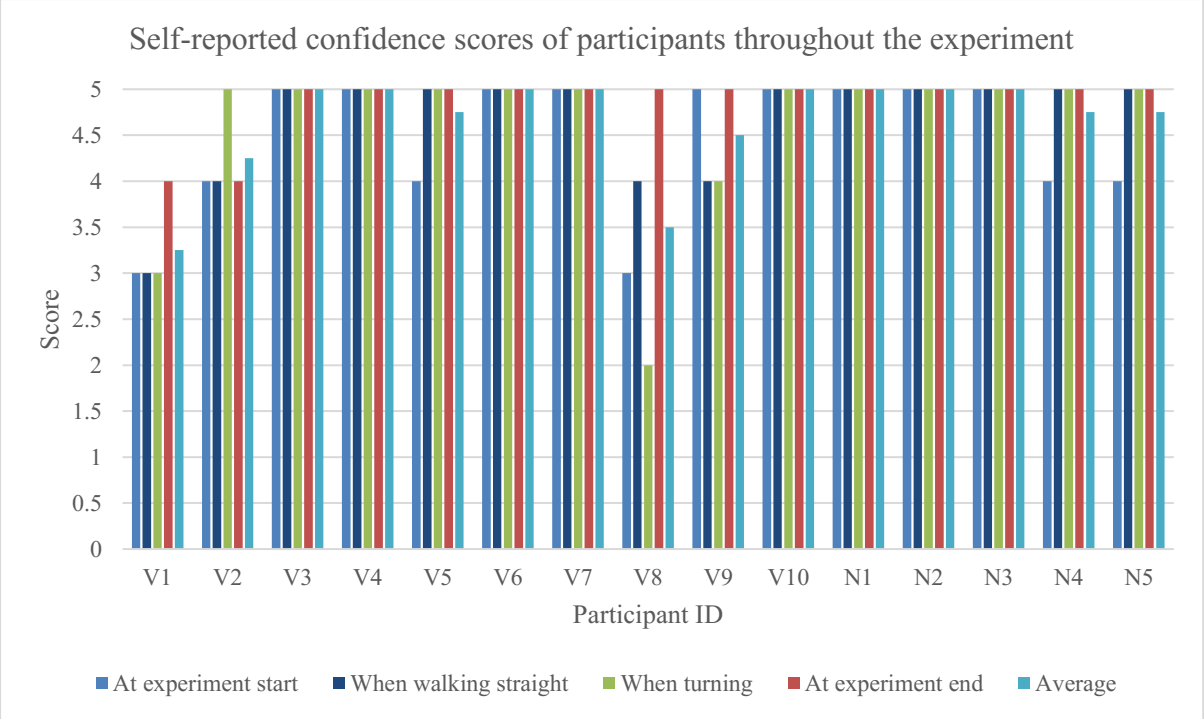


Figure 8.14: Self-reported confidence scores of participants throughout the experiment.

In conclusion, NSPs presented a higher effective speed and average self-reported confidence score than VIPs. Within the VIP group, self-reported visual function scores showed a moderate positive correlation with effective speed, but not with its consistency across sections. However, both NSPs and VIPs (irrespective of demographic) were consistent in their individual performance across each section of the walking path; this is especially the case when compared to the inconsistency of individual VIP performance discussed in Chapter 5. Furthermore, the cane and no cane group yielded similar average walking performances and consistencies across sections. Confidence was not found to be a limiting factor in performance, according to self-reported results, in all but V1 and V8. These individuals scored particularly poorly relative to the remainder of the group. Their interaction with VIPDR is therefore of elevated interest.

8.5.2. VIPDR without Cane Use (System Output)

Figure 8.15 plots both the yaw angle (for heading estimation) and vertical acceleration (for step length estimation) against time for N1. In the plot of yaw angle, the beginning and end of each section is evidenced through the sudden changes of angle (heading). These appear as ‘steps’ as the participant moves from edge to edge across the walking path (such as at 39800 s). In vertical acceleration, this is seen when the acceleration remains at 0 for several seconds while the participant waits for the instruction to traverse the next section. Data beyond 398490 s should be ignored as this proceeds arrival at the last node and represents the removal of the helmet. Its inclusion remains to demonstrate the variation in IMU data beyond the walking task.

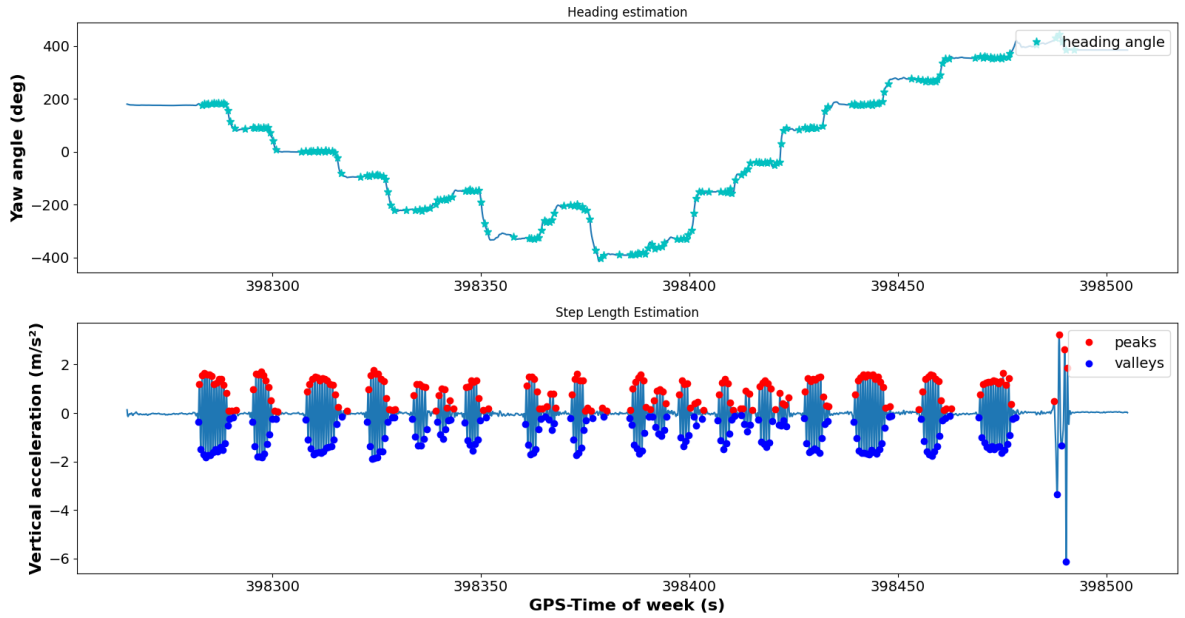


Figure 8.15: Heading and step length estimation for N1.

It is evident that the vertical acceleration presents periodic peaks and valleys (highlighted through red and blue dots, respectively). Moreover, the magnitude of the peaks and valleys is consistent across all sections, ranging between 2 and -2 m/s^2. Disturbances appear between 398350 s and 398400 s, arising from diagonal movement between the outer (A, B, C, D) and inner (E1, E2, E3, E4) nodes of the walking path. These are particularly challenging sections given short walking distances and sudden changes in direction. Figure 8.16 plots N1's effective speed across each walking section to demonstrate their performance here. To aid readability, inner node numbering has been removed.

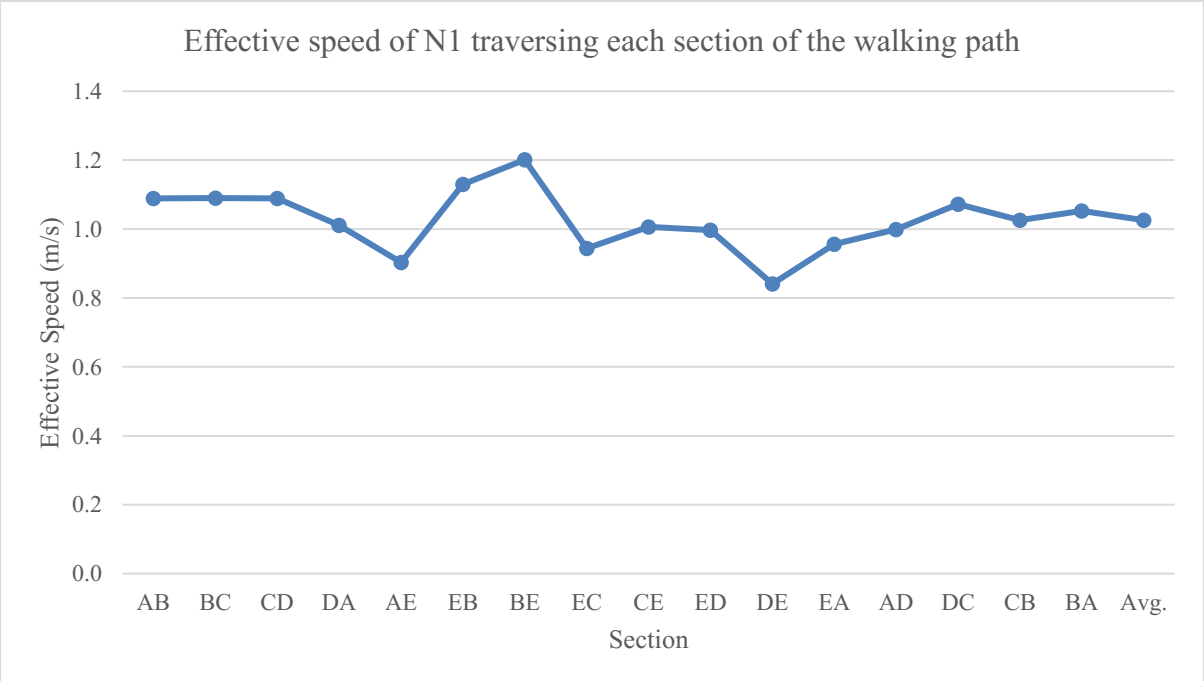


Figure 8.16: Effective speed of N1 traversing each section of the walking path.

Both the minimum (0.8 m/s) and maximum (1.2 m/s) effective speeds were recorded when moving between outer and inner path nodes (DE and BE, respectively). On observing the video footage, N1 traversed the walking path very closely without path inefficiency; effective speed therefore approaches the actual average speed of N1 across each section. The minimum and maximum deviation are only 0.4 m/s apart, and a CV of 8.7% is found in effective speed across the entire walking path. N1 therefore presented an ideal performance, excluding minor disturbances when moving between outer and inner nodes. The use of vertical acceleration for step detection is therefore feasible (and ideal) in this example.

A similar outcome was found for all other NSPs. Yaw angle and vertical acceleration plots against time for N3 evidence this (Figure 8.17). In similar fashion to N1, only minor disturbances are observed as movement to inner nodes occurs. Otherwise, the peaks and valleys of acceleration remain periodic, and the start and end of each section is discernible. The yaw angle remains largely stable per section, with sharp deviation only when moving between sections.

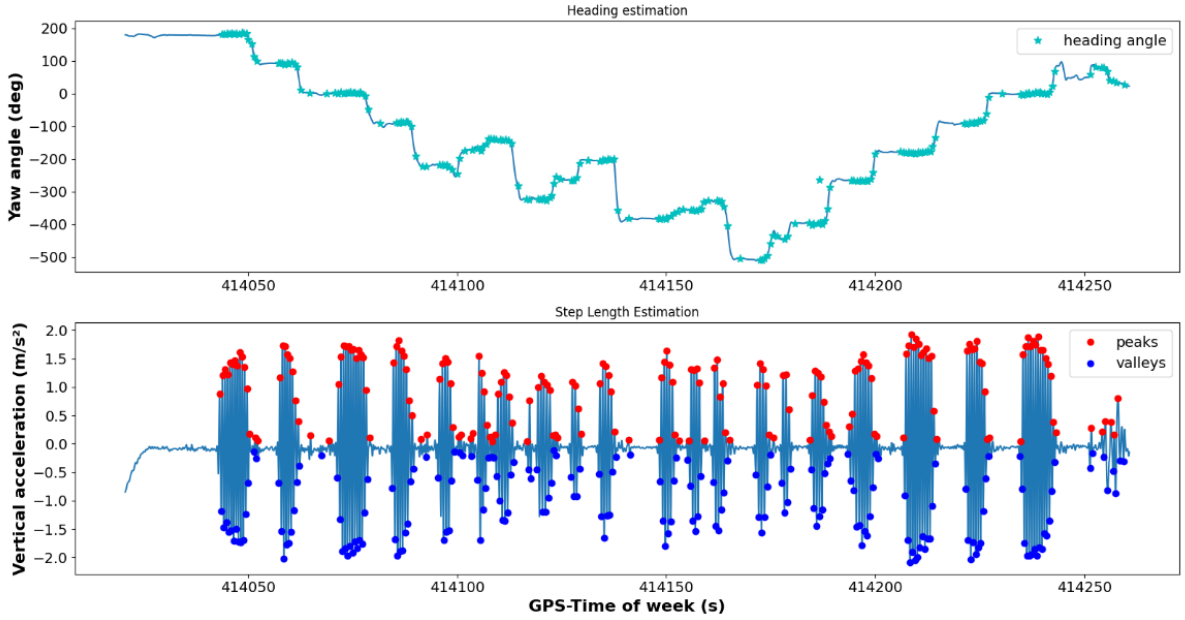


Figure 8.17: Heading and step length estimation for N3.

Figure 8.18 plots N3's effective speed across each section of the walking path. Once again, the minimum (0.9 m/s) and maximum (1.1 m/s) effective speeds occur at outer-inner node pairings (EA and BE, respectively). N3's consistency across each section is greater than that of N1, presenting a CV of 7.0%. Both NSPs similarly yielded no significant deviation from the walking path; the maintenance of an approximately straight yaw angle effectively reflects this.

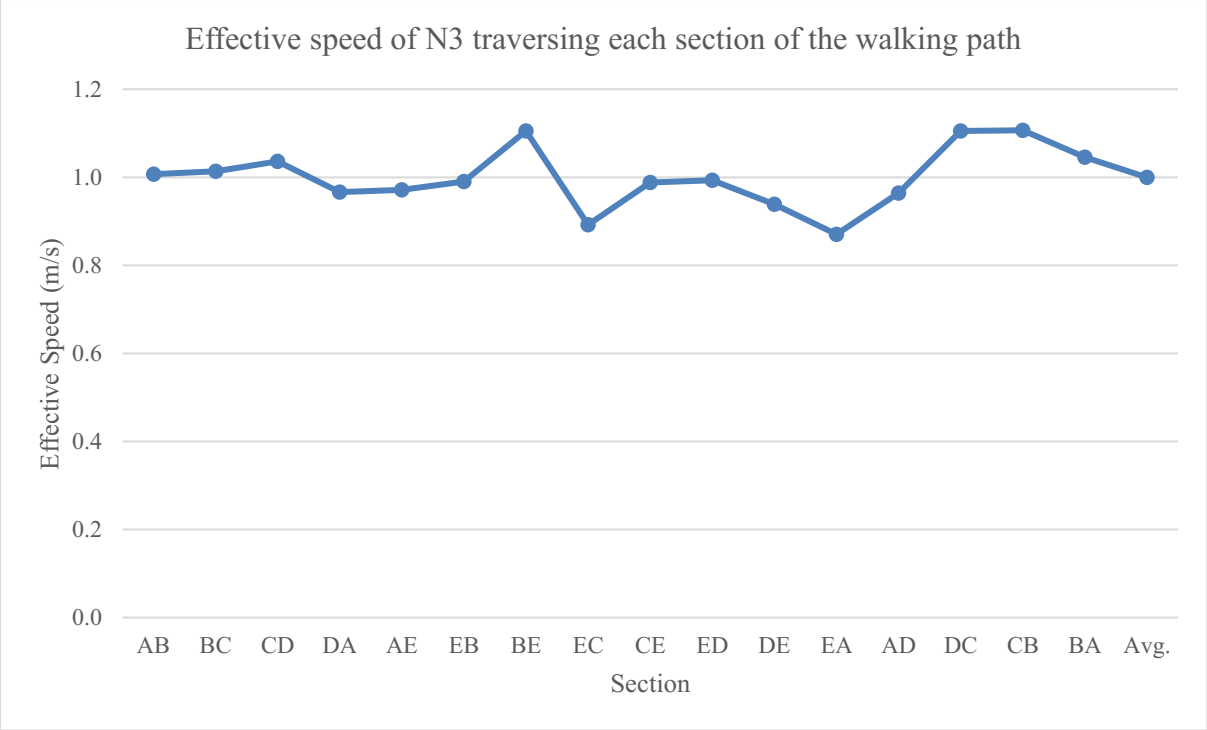


Figure 8.18: Effective speed of N3 traversing each section of the walking path.

Figure 8.19 plots both the yaw angle and vertical acceleration against time for V4. This VIP exemplifies a fast-moving, high-confidence VIP without cane use, yielding an average effective performance above that of the NSP average. V4 finished significantly prior to the automatic stopping of data capture. Heading is well-maintained for each section, with visible rapid changes in direction between them. As is similar for NSPs, the amplitude of vertical acceleration (2 m/s^2) and its periodic nature prevails.

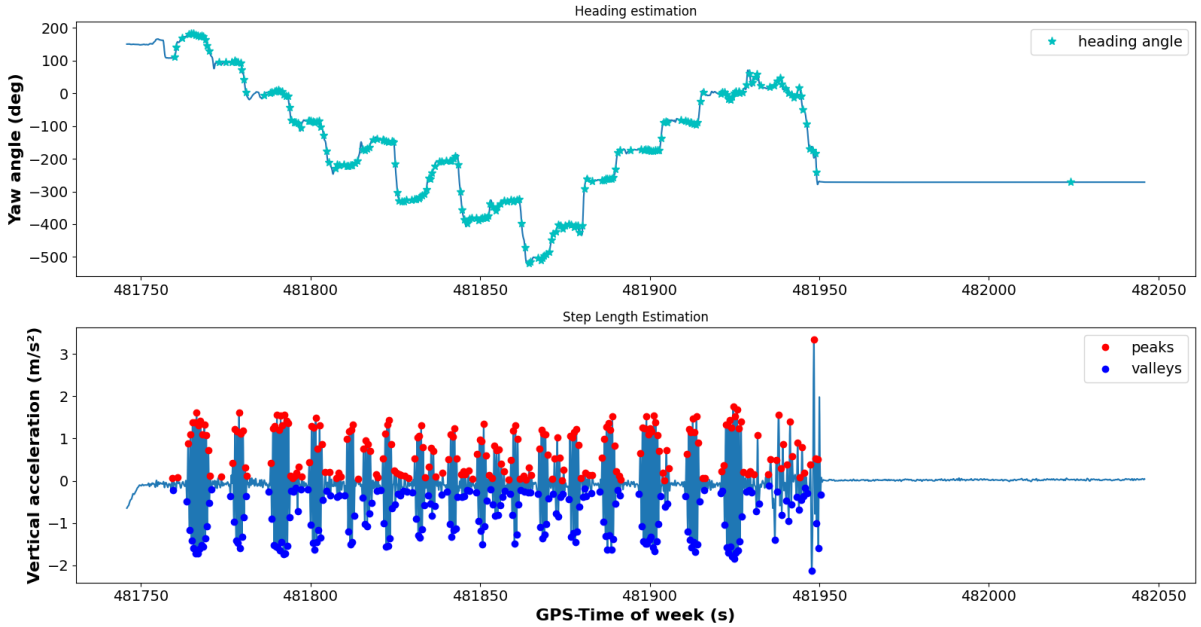


Figure 8.19: Heading and step length estimation for V4.

Figure 8.20 displays V4's effective speed across each section of the walking path. Unlike the examples from N1 and N3, V4 presents a broad variation in effective speed across each section;

CV across sections is found to be 12.9%, with a difference of 0.6 m/s separating the minimum (1.0 m/s) and maximum (1.6 m/s) effective speeds occurring at ED and EB, respectively. The patterns in vertical acceleration and yaw angle remain, however. This is primarily because V4 was able to maintain a high path efficiency through visually detecting the walking path. Vertical acceleration for step detection therefore remains effective for this VIP, showing insusceptibility to their larger performance variation.

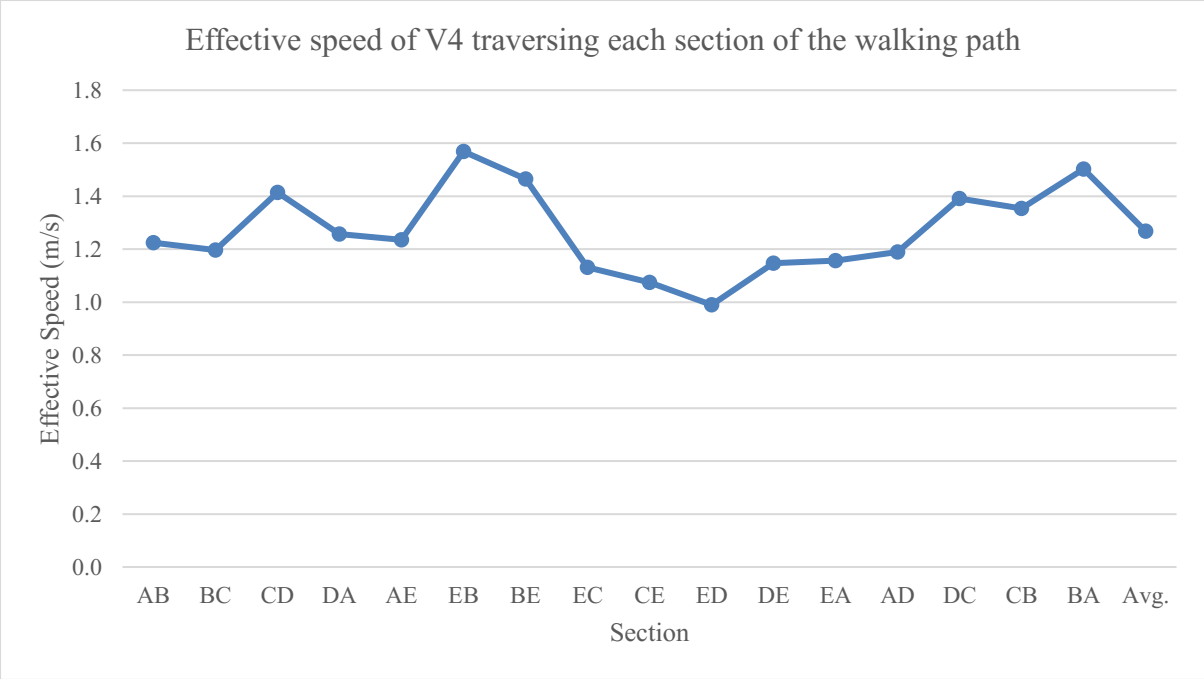


Figure 8.20: Effective speed of V4 traversing each section of the walking path.

A contrasting example of a VIP without cane use is V9. This VIP produced the lowest average effective speed within this demographic. Furthermore, V9 self-reported confidence scores of 4 out of 5 for both walking in a straight line and making turns. This resulted in the lowest average confidence throughout the experiment within this group. Figure 8.21 reflects these reductions in performance. Primarily, an attenuated amplitude of acceleration is sustained at approximately 1.0 m/s^2. Changes in yaw angle require more time than in prior examples, as exemplified by lines with gentler slopes when moving between sections.

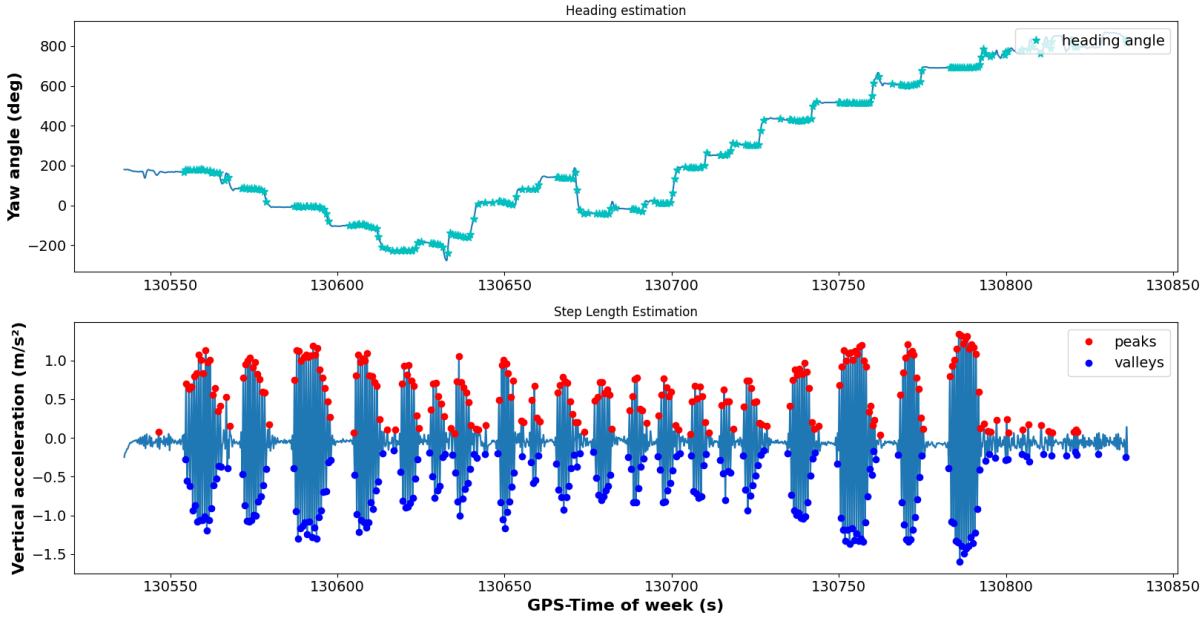


Figure 8.21: Heading and step length estimation for V9.

The periodic nature of vertical acceleration and a stable heading prevail, even with these limitations. This is primarily as V9 maintained a good path efficiency, with no observable hesitation or deviation within the video footage. Figure 8.22 plots V9's effective speed through each section. Relative to V4, V9 yields a smaller deviation of 0.3 m/s in effective speed between a minimum of 0.6 m/s (EA) and maximum of 0.9 m/s (BE). A CV of 11.5% is found; a reduction from V4, but an increase from N1 and N3.

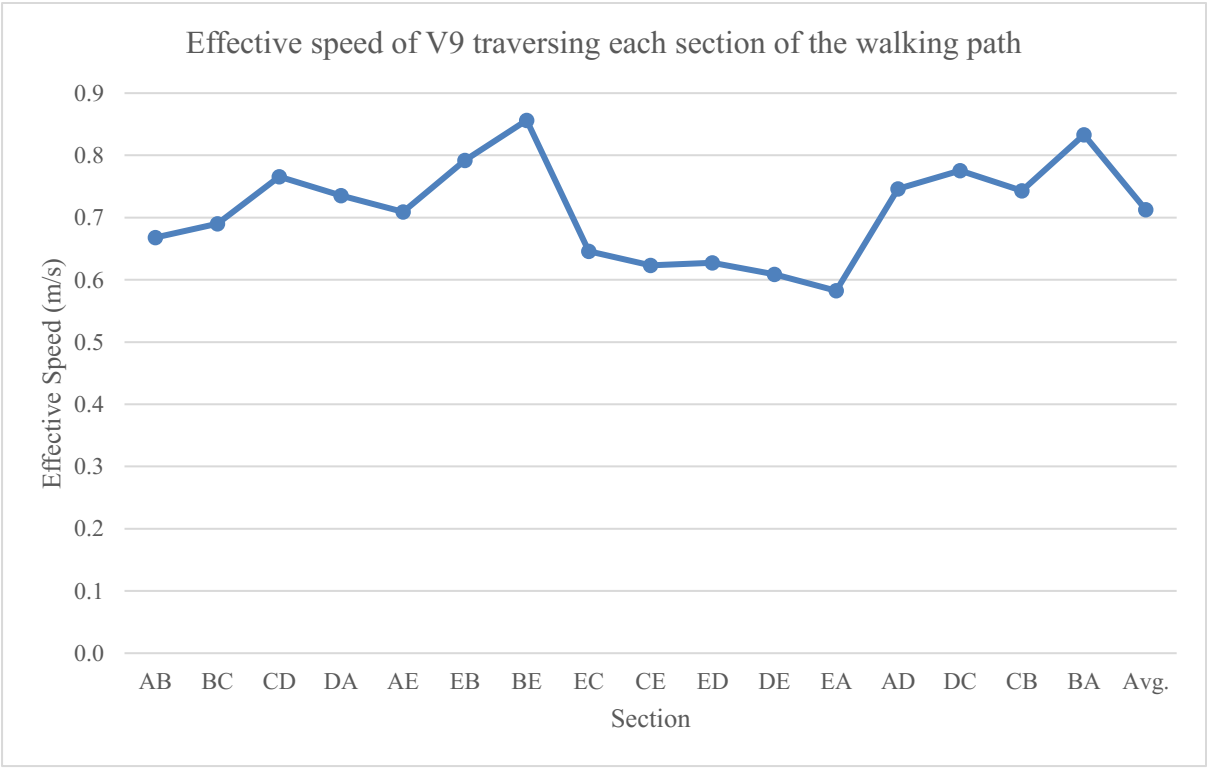


Figure 8.22: Effective speed of V9 traversing each section of the walking path.

Overall, vertical acceleration remains distinguishable in its peak and valleys for both slow and fast-moving examples. However, this is likely a result of these VIPs' better visual function than

those using canes in this experiment's participant sample. Indeed, all examples without cane use yielded high path efficiency and a consistent walking behaviour, although varying in average walking speed.

8.5.3. VIPDR with Cane Use (System Output)

To replicate a control for the cane swing behaviour, the researcher traversed the walking path while maintaining a cane swing per step. The walking path was followed closely without path inefficiency, and pauses were added between sections. This is an ideal scenario, represented by Figure 8.23. Both plots of yaw angle and vertical acceleration against time appear substantially different than their counterparts without cane use. Firstly, the yaw angle presents periodic peaks and valleys, no longer appearing as a straight line. Secondly, while individual sections remain discernible in vertical acceleration, the periodic peaks and valleys are eliminated, Instead, acceleration magnitude fluctuates between 1 m/s^2 and 2 m/s^2, with peaks and valleys appearing without consistency in each section.

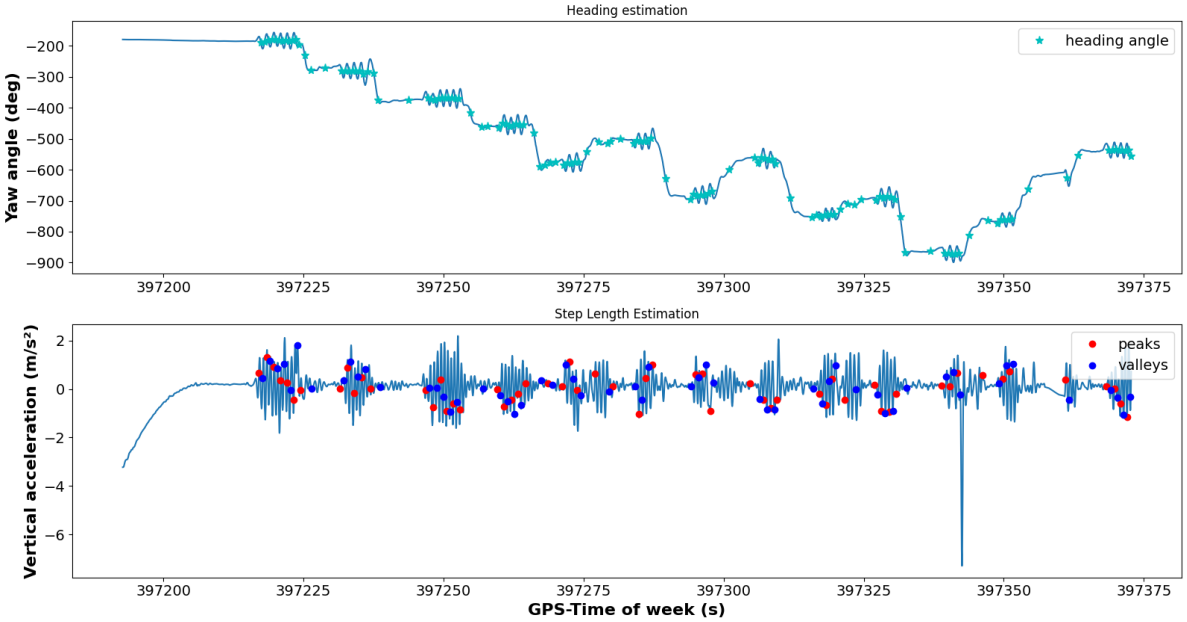


Figure 8.23: Heading and step length estimation for ideal cane use scenario.

As yaw angle is used for step detection in VIPDR's cane use mode, its peaks and valleys are plotted as coloured dots on the graph of vertical acceleration against time. This determines if the periodic step detection from yaw angle corresponds with vertical acceleration. In this instance, it is apparent that the periodic extremes of yaw angle do not relate to those from vertical acceleration. Moreover, the yaw angle fluctuations match closely with cane usage observable within the video footage. For instance, 11 steps of equal length existed when moving between section AB (the first segment of data in the plots commencing at 397220 s). Such is reliably represented by 11 peaks and valleys in the corresponding yaw angle plot.

V7 and V10 are two examples of VIPs using canes and possessing useful vision (CVL). Figure 8.24 plots the yaw angle and vertical acceleration against time for V7. The sporadic vertical accelerations prevail, and the yaw angle maintains a periodic nature as each section is traversed. A new cane behaviour is seen; vertical acceleration spikes in amplitude to 4 m/s^2 at 126140 s, representing a soft collision and recovery with the central pillar. The yaw angle does not appear

disturbed by this sudden variation, represented instead by a peak and valley of a lower magnitude.

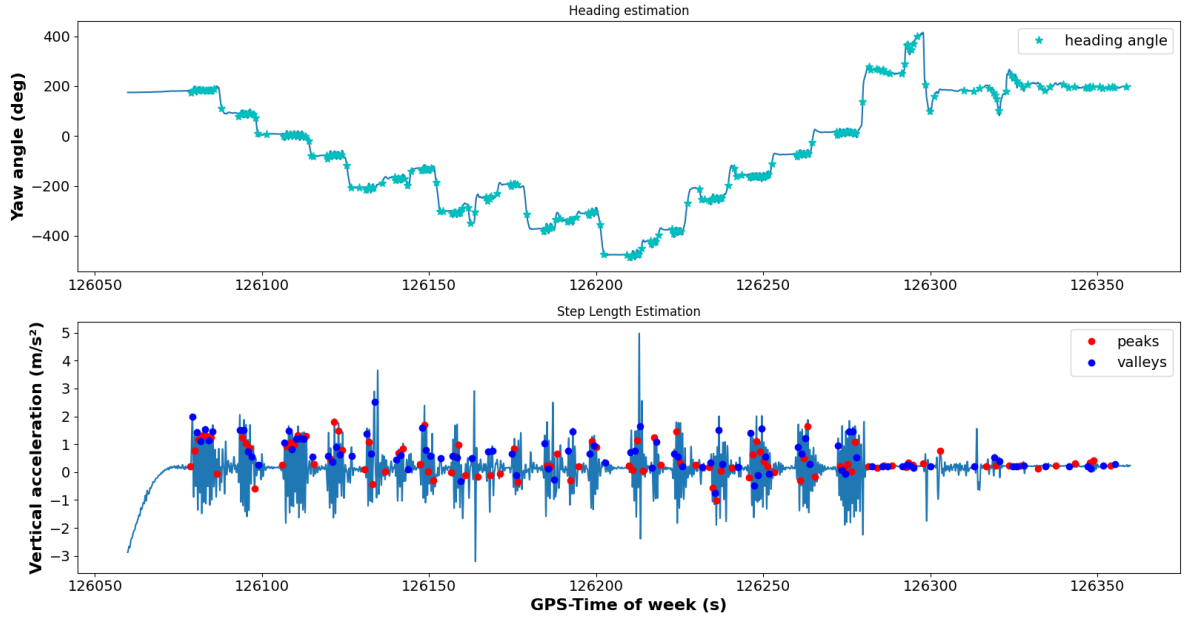


Figure 8.24: Heading and step length estimation for V7 P1.

Two passes were conducted with this VIP. Figure 8.25 represents the corresponding plots of yaw angle and vertical acceleration against time. This VIP was very consistent with their behaviour in both passes, and the same periodic yaw angle osciliation is therefore visible. The acceleration peak of 6 m/s^2 at 126610 s results from an aggressive cane movement when moving between sections to avoid contact with the central pillar. Once again, the yaw angle does not significantly fluctuate from this disturbance.

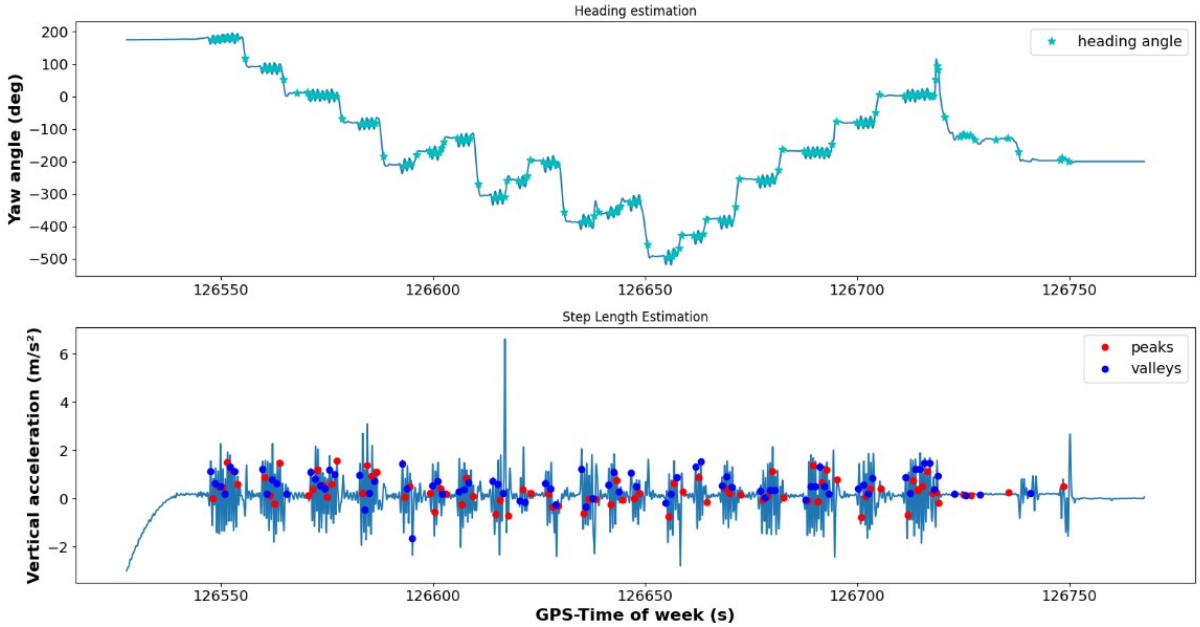


Figure 8.25: Heading and step length estimation for V7 P2.

Figure 8.26 plots V7's effective performance for each section across both passes. The substantial similarity between passes is confirmed. Moreover, a high consistency exists between sections; a CV of 8.3% and 8.8% is found for the first and second pass, respectively.

This is comparable to the consistency of NSPs without cane use. This VIP therefore presents an ideal scenario for yaw angle-based step detection in VIPDR; cane use was stable without path inefficiency (observable from the video footage), and minor discrepancies disturbed vertical acceleration rather than yaw angle.

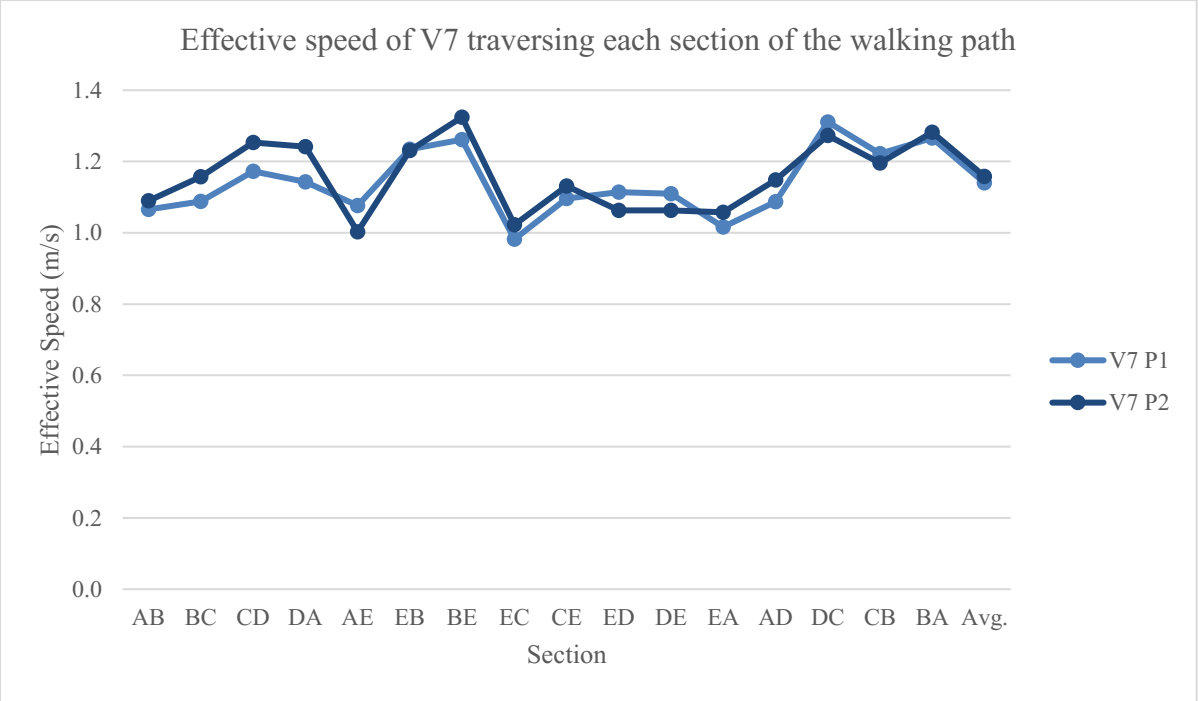


Figure 8.26: Effective speed of V7 traversing each section of the walking path.

V10 is a fast-moving cane user with CVL. Figure 8.27 presents the output yaw angle and vertical acceleration plotted against time. The peaks and valleys of yaw angle remain apparent in this instance and are similar to those from both passes by V7. Furthermore, no anomalous vertical acceleration peaks prevail as no sudden cane movements or collisions occurred. A difference between V7 and V10 is that, when walking, V10 would begin moving their cane prior to their first step. This is characterised by a peak and valley immediately upon a change in heading between sections, visible at 15460 s, and in all sections beyond 15560 s. Contrarily, V7 would step prior to moving their cane, and this step would therefore be missed by VIPDR (represented by a longer flat yaw angle line at the start of every section).

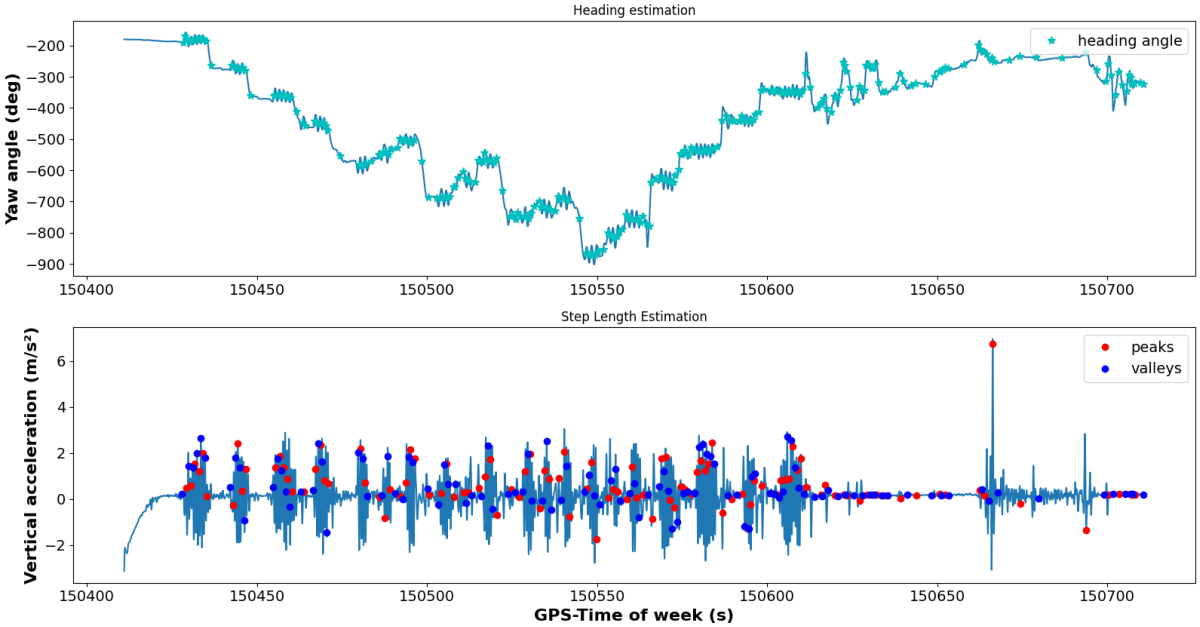


Figure 8.27: Heading and step length estimation for V10.

Beyond this variation, the visible cane use behaviour of both V7 and V10 in the video footage was very similar, portraying an ideal step-per-swipe with identical swipe widths. Additionally, both VIPs closely traversed the walking path, yielding an effective speed that approached their actual walking speed. Figure 8.28 illustrates this, portraying a representative image of the maximum swipe width of V7 and V10 as they moved across all sections. It can be seen that the extreme of the pendulum-like cane swipe occurs as the next step begins, representing an effective yaw angle behaviour for VIPDR.



Figure 8.28: Representative cane swipe width of V7 (left) and V10 (right).

Figure 8.29 plots V10's effective speed across each section of the platform. Effective speed generally increased as V10 progressed across the walking path, and the highest effective speeds were all recorded in the final three sections. The aforementioned cane behaviour introduced by V10 towards the final sections of the walking path may therefore have been an artefact of this variation. Notwithstanding this, the overall consistency across each section remained high with a CV of 9.8%, comparable to that of V7 and NSPs without cane use.

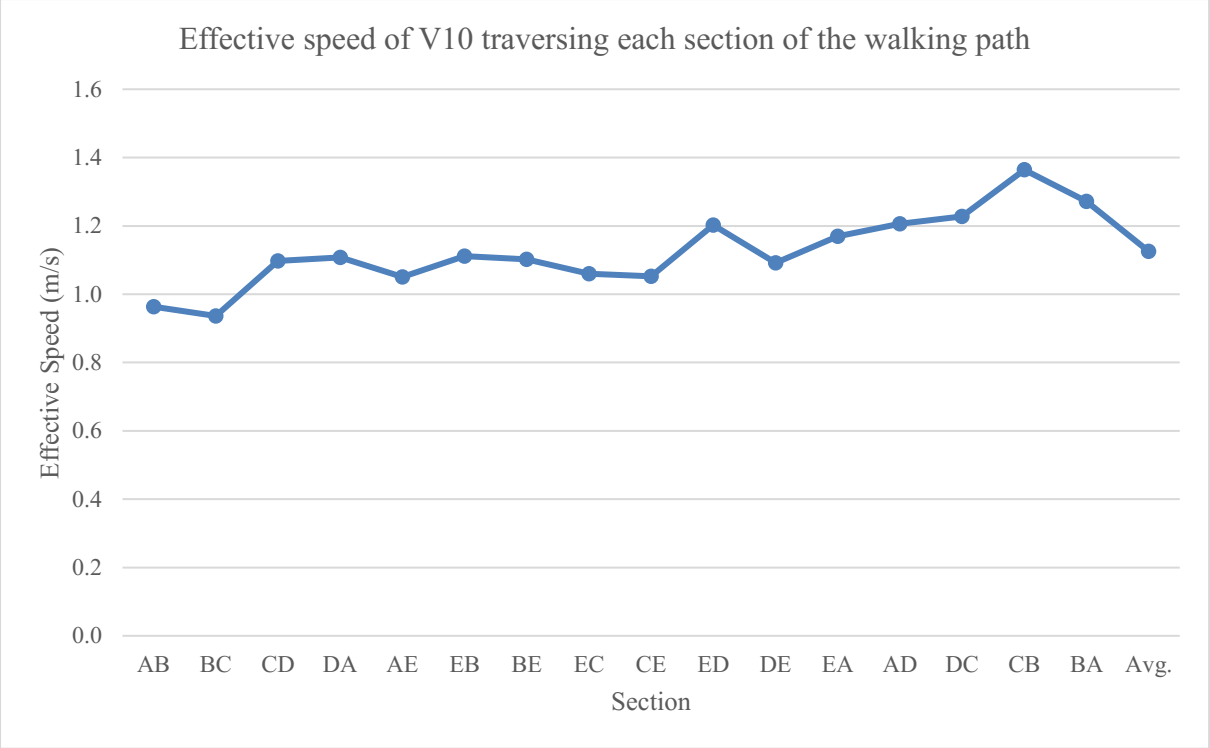


Figure 8.29: Effective speed of V10 traversing each section of the walking path.

V1 and V8 are examples of VIPs with cane use within the B group. From the preceding observation of walking behaviour, these VIPs presented the lowest confidence, visual function, and associated effective speeds of all participants. Figure 8.30 plots the yaw angle and vertical acceleration against time for V1. The first discrepancy when compared to prior VIPs with cane use is the variation of yaw angle; the periodic nature of peaks and valleys continues, but the consistency of amplitude does not. Moreover, the vertical acceleration includes more anomalies (sudden peaks and valleys) from unstable cane movement.

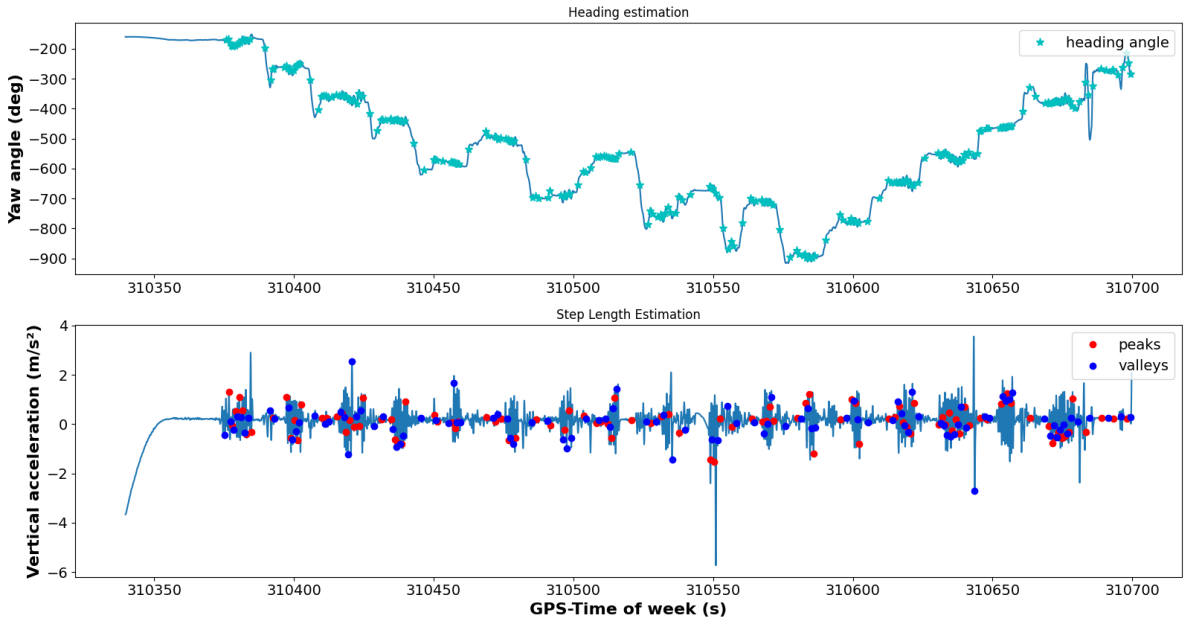


Figure 8.30: Heading and step length estimation for V1.

Observation of the video footage qualifies these findings. V1 moved inefficiently across the walking path, often deviating in both directions from the effective walking line. Such is exemplified in Figure 8.31. This explains the gradient in heading (when averaging peaks and valleys), exemplified at the section starting 310460 s. Moreover, cane swipes were not consistent per step, with instances of the cane being held straight (or minimally moved) upon deviation from the walking line.



Figure 8.31: Path inefficiency and unsynchronised cane motion by V1.

To provide greater detail on the implications to yaw angle for step detection, Figure 8.32 plots only the yaw angle against time for V1. The valleys and peaks of yaw angle are highlighted through differently coloured dots. Instances of valleys exceeding peaks within a single section exist within the first four sections (outer walking path), between 310380 s and 310440 s. The density of peaks and valleys is higher than in the data proceeding this where movement to inner nodes occurs. The identification of steps becomes difficult here, particularly at 310450 where the cane is not moved while steps are taken, followed by several faster movements to prevent collisions with the central pillar.

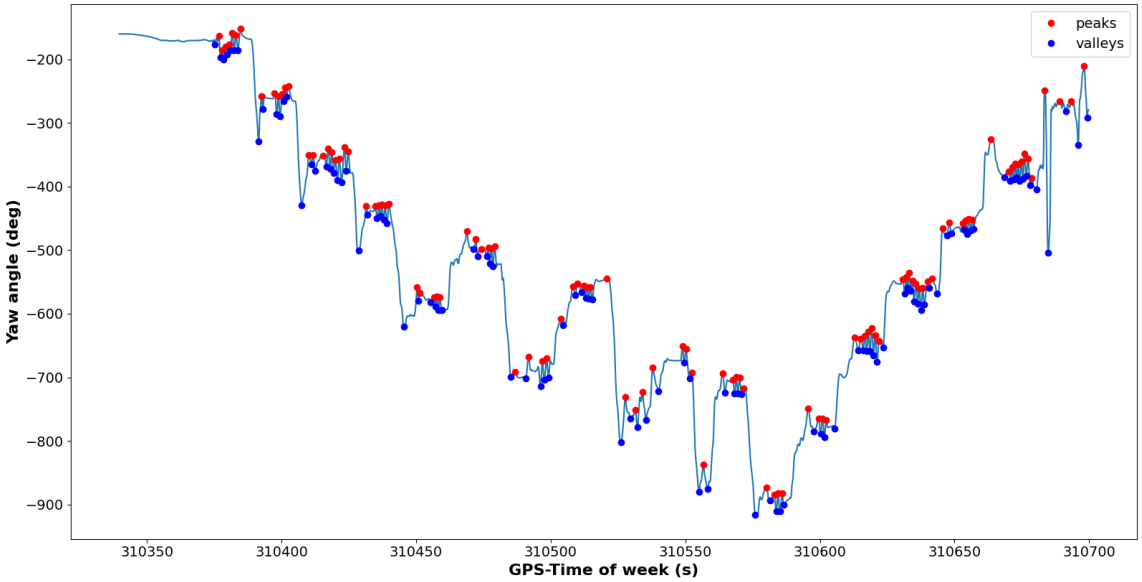


Figure 8.32: Variation in yaw angle for V1.

Figure 8.33 provides a plot of yaw angle for V7 by way of a contrasting example. It is evident that the variation of yaw angles is significantly more consistent, with peaks and valleys maintaining a similar cadence and amplitude for each section. While there is disturbance in the data as shorter movements towards the inner walking path occur (at 126140 s), the 'clusters' of cane movement prevail and individual sections can still be distinguished.

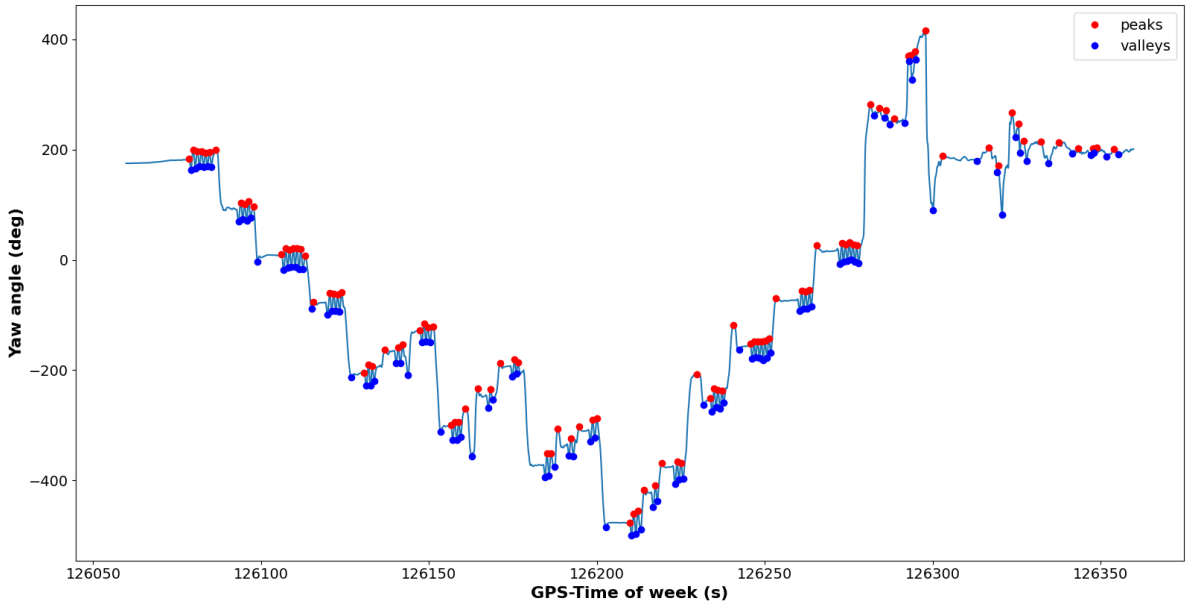


Figure 8.33: Variation in yaw angle for V7.

V1's effective speed across sections is presented in Figure 8.34. While an 0.4 m/s variation exists between the minimum (0.6 m/s) and maximum (1.0 m/s) value, the CV of 12.1% remains comparable to that of VIPs without cane use (and is only marginally greater than that of V7 and V10). The variation of effective speed, in this instance, is therefore not indicative of the instability of cane movement demonstrated by V1.

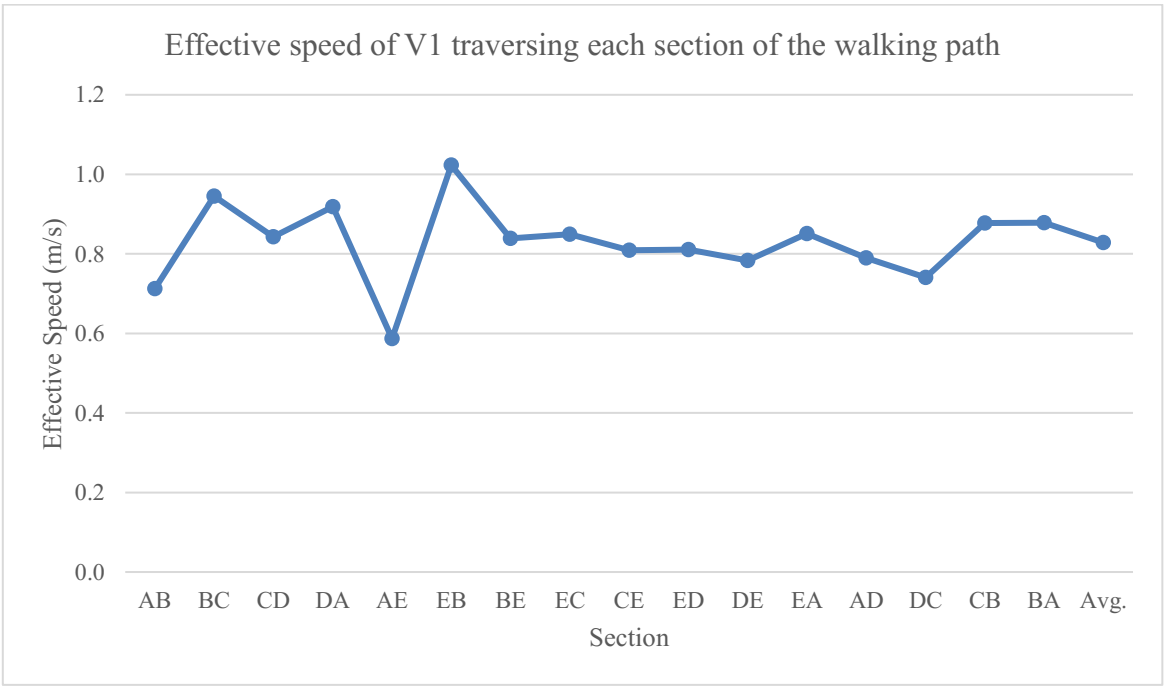


Figure 8.34: Effective speed of V1 traversing each section of the walking path.

Finally, V8 presents a similar performance to V1, demonstrated in the plot of yaw angle and vertical acceleration against time (Figure 8.35). The characteristic anomalies in vertical acceleration of unstable cane use are present. Additionally, while periodic yaw angle peaks and valleys prevail in the outer walking path (127600 s to 127680 s), this is reduced as traversal of the inner sections proceeds.

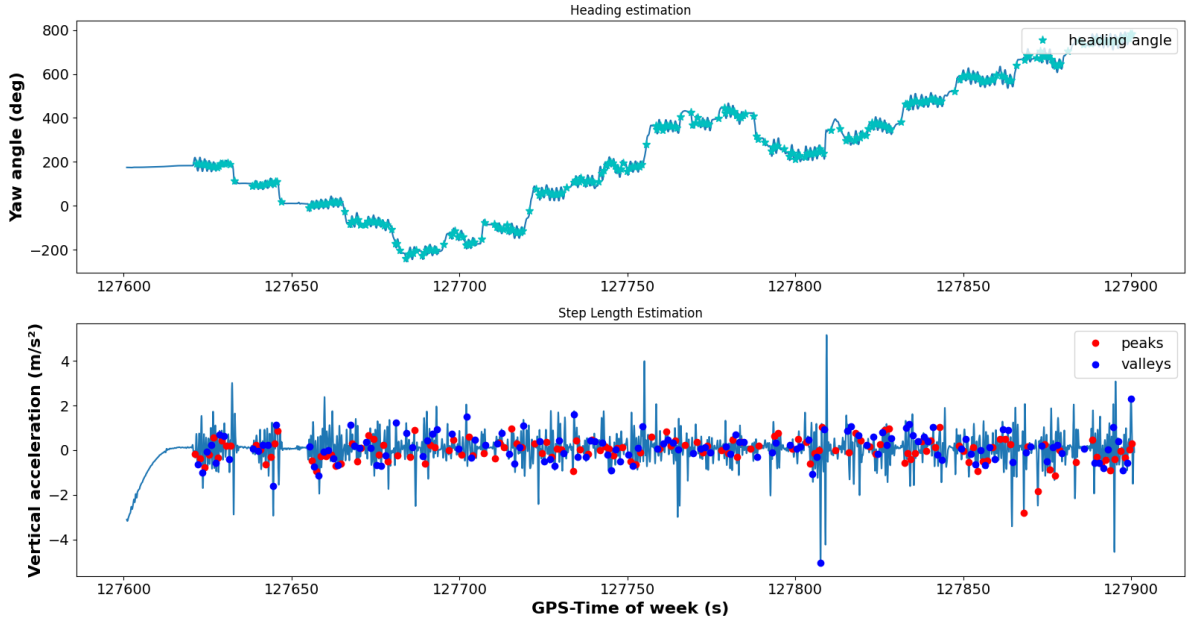


Figure 8.35: Variation in yaw angle for V8 P1.

Of interest is a further decline in cane use stability upon returning to the outer walking path (the final four sections) beginning at 127800 s. Figure 8.36 plots the yaw angle variation, with peaks and valleys highlighted, for V8. Examples at 127820 s and 127850 s demonstrate a gap in the repetition of peaks and valleys, with the example at 127820 s showing a change in overall heading. Here, the preceding peaks all fall below the proceeding valleys.

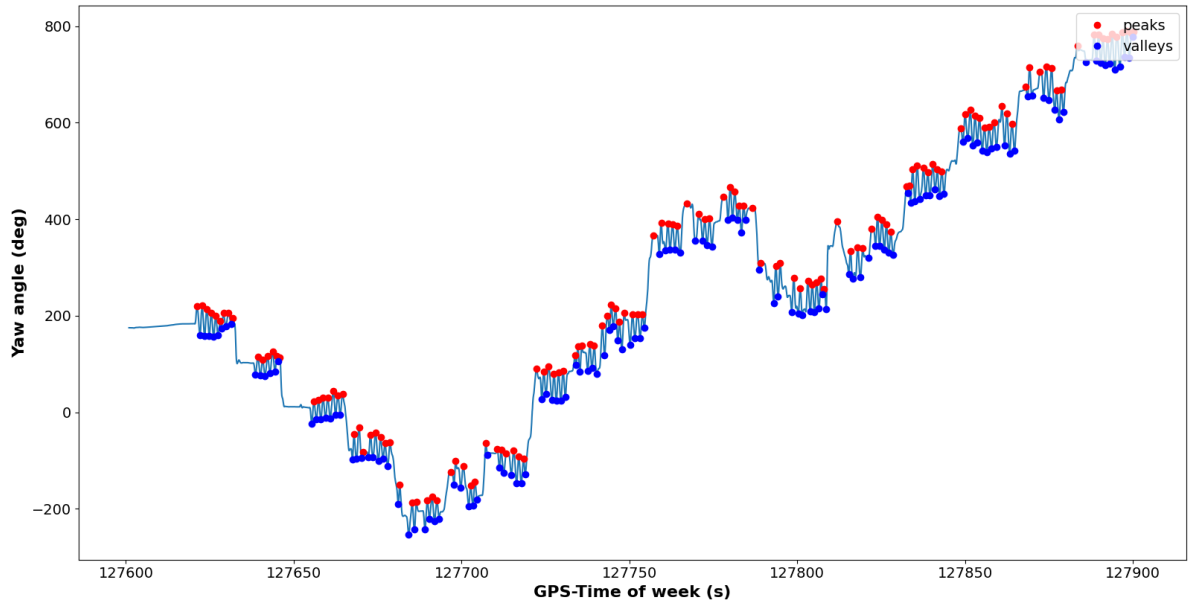


Figure 8.36: Variation in yaw angle for V8 P1.

On both occurrences, V8 executed a much wider single cane swipe on deviating and correcting their heading to return to the walking path. The images in Figure 8.37 evidence this from the video footage. Moreover, as was conducted by V10 towards the end of the walking path, V8 would swipe their cane prior to taking their first step within the final sections. Interestingly, this behaviour was less prevalent in the earlier sections of the walking path, shown by a flat yaw angle line without peaks and valleys prior to movement.

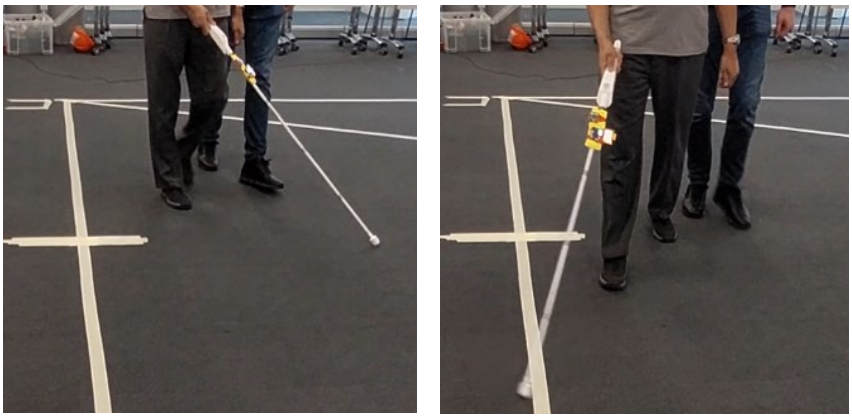


Figure 8.37: Large and inconsistent cane movement by V8.

To determine the repeatability of this behaviour, another pass of the walking path was conducted for V8. Figure 8.38 displays the yaw angle variation in this instance. Here, this swiping behaviour occurred in every section, including those in the earlier stages of the walking path. It is uncertain as to why these did not occur in earlier sections of the first pass. In using yaw angles, VIPDR is therefore vulnerable in registering a step without user movement.

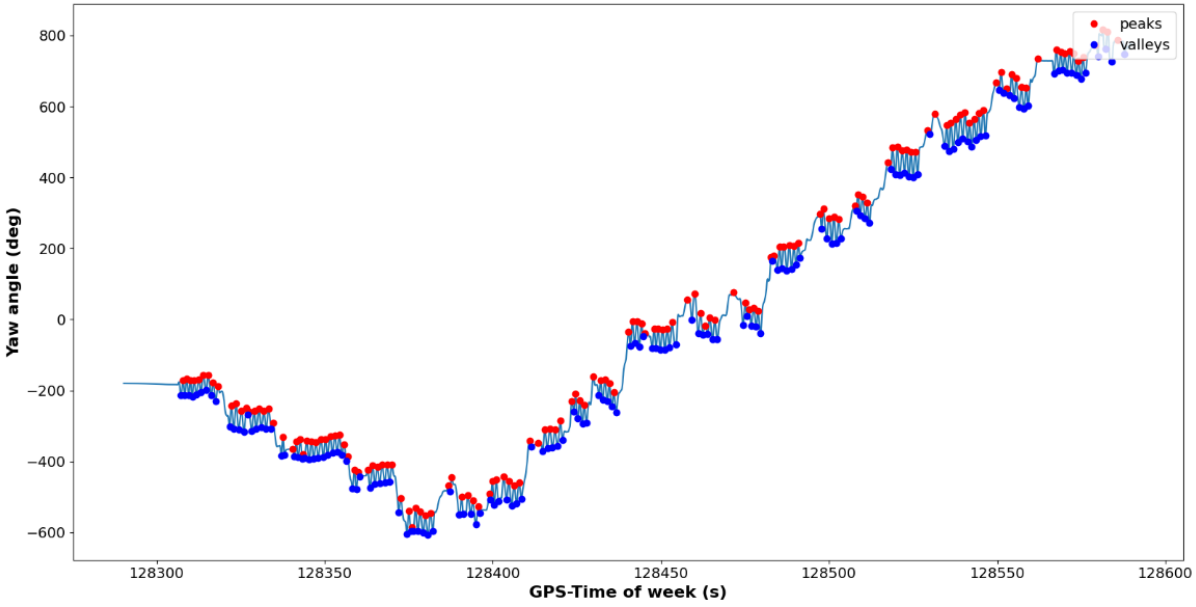


Figure 8.38: Variation in yaw angle for V8 P2.

The variability of V8's effective speed is plotted in Figure 8.39. A CV of 10.6% and 12.1% between sections is calculated for the first and second pass, respectively. Indeed, this variation remains similar to that from all prior examples. The usefulness of effective speed in determining the behaviour of cane users, within this experimental sample, is therefore limited.

In considering both V1 and V8's results, this is likely as effective speed did not represent actual walking speed given path inefficiencies.

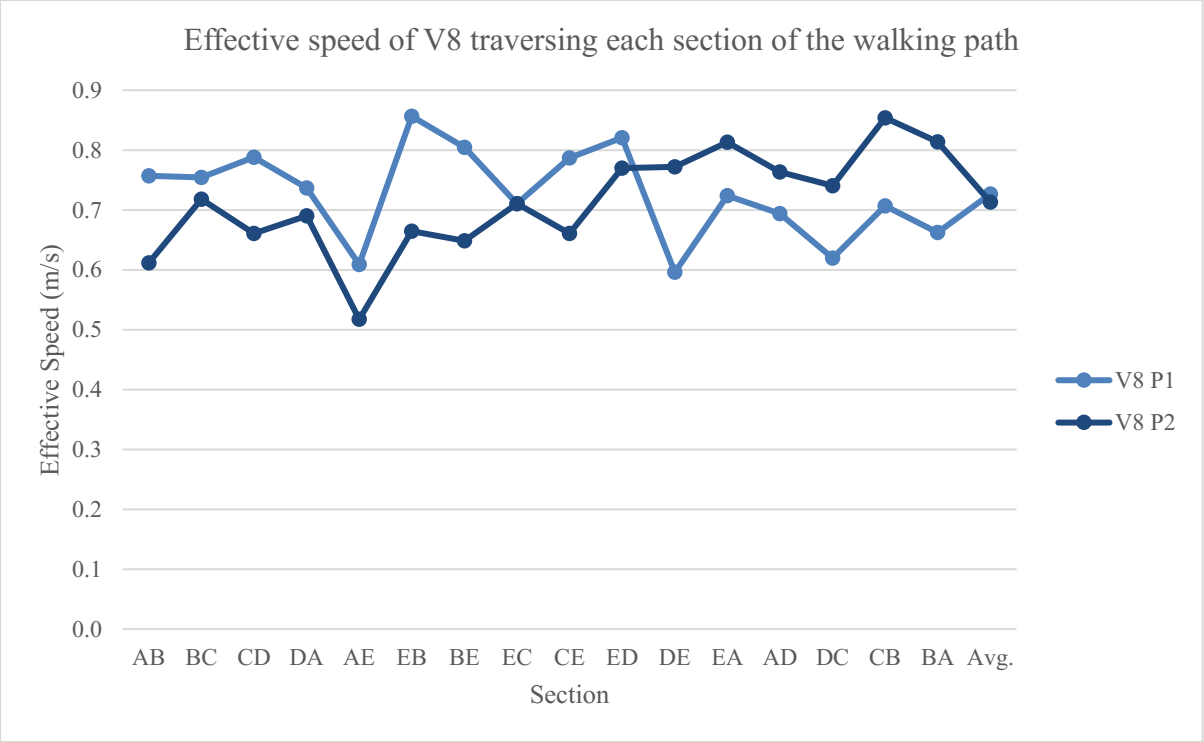


Figure 8.39: Effective speed of V8 traversing each section of the walking path.

In summary, vertical acceleration cannot be used by VIPDR when positioning a user with cane use. Instead, yaw angle presents a significantly more periodic, and therefore predictable, data source for step detection. However, yaw angle period and magnitude are more sensitive to minor variations in VIP behaviour, more so than vertical acceleration without cane use. This vulnerability is worsened by this particular experimental sample; cane users possessed worse visual function than their counterparts without cane use. As a result, path efficiency is visibly deteriorated in instances with cane use. Variations in effective speed could not represent, or explain, these deviations. Moreover, unique cane movements by each VIP, such as swiping prior to movement, expose failure modes within this implementation of VIPDR.

8.6. Conclusions on the Development and Validation of a Navigation System to Improve Visually Impaired Mobility

In conclusion, the findings and requirements delivered by this thesis contributed the foundations for the development of a navigation system for visually impaired people. The requirements were first captured by the system's functional architecture, and a novel method of positioning the VIP according to their behaviour was then proposed. This was termed VIPDR, an IMU-based positioning technique that integrates with Bluetooth AOA positioning.

VIPDR accommodates several inputs and two different usage modes for VIPs with and without cane use. The fundamental difference between each is the method of step detection. Without cane use, the periodic variation of vertical acceleration is employed for step detection. With cane use, this shifts to a reliance on periodic yaw angle variation. In preliminary experimentation by Alghananim et al. (2022), basic system functionality was guaranteed for

further testing with visually impaired participants. The experimental principles validated through Chapter 5 of this thesis were then employed in mobility course construction, participant selection, and the data analysis methodology.

Practical experimentation determined that a strong relationship exists between the peaks and valleys of vertical acceleration for step detection without cane swing. This was particularly prevalent in NSPs that presented a very stable walking behaviour; here, a predictable periodic vertical acceleration was found. Concurrently, the yaw angle data was characteristic of a stable walking behaviour without sudden changes in direction. This was true for VIPs without canes, even when minor reductions in walking consistency prevailed.

When attached to a cane and with swing mode enabled, the vertical acceleration was destabilised. The periodic feature between peaks and valleys was diminished, and the use of vertical acceleration for step detection became unfeasible. Contrarily, the peaks and valleys of yaw angle were periodic with the swing of the cane. Variations in yaw angle were therefore more useful for step detection. However, VIPs were not consistent with their cane use in that some did not conduct a swipe per step (weakening the peak-to-valley yaw relationship per step).

Moreover, the sample of VIPs using canes in this experiment included two with low walking confidence. This led to a relatively more erratic walking behaviour than that of the VIPs without cane use. Particularly, deviation from the walking path was more prevalent, as was hesitation leading to sudden acceleration and deacceleration. The periodic stability of the yaw angle was further reduced within this group.

Therefore, VIPDR's use of vertical acceleration for users without canes, and yaw angle for users with canes, is validated. This is particularly as vertical acceleration is not useful for step detection in cane swing. However, the scenarios presented within this experimentation are ideal; knowledge, lighting, and ground surface are controlled. Problematically, these relationships are shown to weaken in VIPs outside their optimal behaviour. Notwithstanding these limitations, the use of vertical acceleration and yaw angle in VIPDR presents a novel foundation for VIP navigation systems to build on. Moreover, the applicability of this thesis to the lifecycle of system engineering is successfully demonstrated, from requirements derivation to validation following controlled experimentation.

9. Thematic Analysis of the Challenges, Motivations, and Coping Mechanisms of Visually Impaired People in Different Environments

A critical literature gap identified in Chapters 5 and 6 is insufficient evidence on the challenges endured by a visually impaired person in real-world environments. To address this, semi-structured interviews are conducted with the participant group detailed in Chapter 8. Section 9.1 begins with the methodology employed and its justification. Section 9.2 proceeds with results and discussion for each of the 25 environments investigated. Section 9.3 summarises findings through themes for each environment. Finally, it is concluded that the same visually impaired person experiences different challenges according to their environment, and that a coping mechanism in one may not be effective in another.

9.1. Introduction and Justification of the Data Collection and Analysis Methodology

9.1.1. Review of Data Collection Methods

The experiences of visually impaired people in different environments have not been sufficiently detailed in literature. This is particularly in comparing the challenges and their variation for a given individual, as recommended in Chapter 7. To understand individuals' challenges and motivations, it is important that an open discussion can be had. Particularly, one that allows the individual to elaborate on their thoughts without fear of repercussion or judgement from others (Acocella, 2011). Five different collection methods are therefore reviewed, including their limitation, prior to execution (Table 9.1).

Method	Description	Limitations
Closed-Questionnaires	Participants are required to respond to a series of questions using a set of pre-defined answers.	Predefined answers would restrict the response the participants can provide and does not allow for in-depth knowledge to be shared by the participant (O'Cathain & Thomas, 2004).
Open-Questionnaires	Participants are required to respond to a series of questions by writing their own responses.	Visual clues indicative of sentiment, such as expressions and tone of voice, are diminished. As is the opportunity for clarification or elaboration of certain points by the interviewee (O'Cathain & Thomas, 2004).
Focus groups	A group of individuals discusses their thoughts and understanding of topics introduced by the researcher (acting as a moderator) in a shared space.	Common opinions between individuals are often discussed in more detail compared to those that they may not agree with. Individuals may also limit the points they raise, either because they are not comfortable in discussing them as a group or are concerned with others' disapproval. Members may interrupt one another. This can be off-putting for some individuals and might limit the information they share (Acocella, 2011).
Observations	The researcher observes individuals operating in each environment.	Logistical impasses arise in attending the listed environments with 15 participants, particularly considering social distancing and health concerns.

Table 9.1: Review of candidate data collection methods.

The final collection method reviewed is the use of individual interviews. This is a verbal interchange between two individuals where one (the researcher) asks the other (the interviewee) questions to elicit information from them (Longhurst, 2016). Individual interviews address the limitations of the priorly reviewed collection methods; non-verbal clues can prevail, and interviewees are provided greater privacy to express their thoughts without the pressure of a group setting (Opdenakker, 2006).

A limitation of individual interviews is their time-consuming nature. Moreover, determining the number of interviews required to reach information saturation is a difficult process (Adams, 2015). The direction of the interview is dependent on the questions and follow-ups presented by the interviewer, introducing potential for bias and subjectivity. Interviewer behaviour may also alter the responses provided by participants (Opdenakker, 2006). Cohen et al. (2007) explains that interviewees may not be forthcoming with their responses, withholding detail or truthfulness if so preferred. The interview methodology employed is therefore controlled, within reason, to mitigate these risks.

9.1.2. Interview Structure and Setting

Semi-structured interviews including probes were employed. This enabled freedom of discussion and follow-up when additional detail was required (Harrell & Bradley, 2009). Interview questions focused on determining interviewee confidence in different environments, and the underlying reasons as to such confidence. The environments included were, in order:

1. Outdoor (general)
2. Indoor (general)
3. Street
4. Open space (park, beach)
5. Shared space
6. Bus stop
7. Bus terminal
8. Taxi rank
9. Through station
10. Terminating station
11. Airport
12. Shopping centre
13. Commercial unit
14. Restaurant/Eatery
15. Hospital
16. Local clinic
17. Public house
18. Museum
19. Theatre/Cinema
20. Stadium
21. Office/University building
22. Private dwelling
23. Gym
24. Sports hall

25. Hotel

These environments were included as they represent a wide range of spaces in which the visually impaired person is likely to operate in daily activity (Spinks et al., 2021). Participants were also provided with the opportunity to openly add any comments about environments or behaviours that they felt were not included in this list. Confidence for each environment was determined by asking each participant how they felt when operating in each environment on a 5-point Likert scale where each number represented the following:

1. Very poor
2. Poor
3. Neutral
4. Good
5. Very good

Participants were then encouraged to comment on the reasoning for their answers, although prompts were not given as to avoid interviewer bias. When further detail was required, additional questions were asked.

The participant sample was that described Chapter 8. These participants had taken part in the mobility testing within the same session. Participants were obtained through selective sampling; judgement was made to select individuals believed to be most beneficial to the study. Given the selection of participants from the visually impaired community, the fear of lack of diversity and variation within the sample can be dismissed. This approach allowed for participants with lived experiences that would be willing to speak on sensitive topics. However, the range of visual impairments tested within the sample does not allow for statistical significance. Rather, an indication is provided as to how challenges and motivations can vary within an environment according to the type of visual impairment.

All interviews were conducted in person between 16th March 2022 and Tuesday 29th March 2022. Their length varied from 30 minutes to 60 minutes depending on the depth of answers provided by the interviewee. Efforts were made to ensure a positive and relaxed environment, and equal engagement was attempted for expected and unexpected responses. Responses were manually transcribed and verbally repeated to the interviewee for their review and validation. Transcripts were labelled with the participant ID assigned in Chapter 8 to protect confidentiality and minimise researcher bias.

9.1.3. Thematic Analysis of Interview Data

The interviews provided a substantial volume of data. A thematic analysis is therefore employed, enabling the conversion and organisation of this data into concise summaries of findings, termed themes (Braun & Clarke, 2006; Erlingsson & Brysiewics, 2017). These enable the identification of patterns within data, an ideal characteristic for matching the challenges experienced by individuals across several environments.

The analysis of results is conducted in two stages. The first involves processing ratings for each environment to determine mean, deviation, and coefficient of variation, allowing for the ranking of environments from worst to best. The second is the in-depth coding of each response to determine common themes, allowing for behaviours in each environment to be classified,

quantified, and ordered. These are then compared to the processed participant ratings to assess continuity and identify patterns.

To code responses, guidance is sought from Braun and Clarke (2006), and Erlingsson and Brysiewics (2017). As suggested by Erlingsson and Brysiewics (2017), the process is approached with an open mind, and unexpected findings are not dismissed. The transcripts are first read numerous times to gain an understanding of their content and structure. Following this, they are divided into smaller parts (units). Speech disfluencies and repeated words are then removed intuitively to aid readability and analysis. Otherwise, responses are not altered, shortened, or modified to ensure that the exact wording used by participants is captured. A code is then assigned to each unit, acting as a label to identify the unit's meaning. Several codes could be assigned to a single unit.

Codes are then grouped into categories through a semantic and latent approach to form themes. These are noted and tabulated. A second pass of the units is then conducted, and each is compared to the tabulated themes, marking each theme that appears. Units are further classed into those from the CVL, PVL, B, and NSP groups to identify if visual function had any impact on the themes observed. 19 themes emerge from this analysis, including:

- Dependence on familiarity
- Obstacles - Positive
- Obstacles - Negative
- Ground condition - Positive
- Ground condition - Negative
- Congestion - Positive
- Congestion - Negative
- Signage - Positive
- Signage - Negative
- Lighting, colour, contrast - Positive
- Lighting, colour, contrast - Negative
- Auditory reference - Positive
- Auditory reference - Negative
- Boundaries - Positive
- Boundaries - Negative
- Visual function - Positive
- Visual function - Negative
- Sighted assistance - Positive
- Sighted assistance - Negative
- Technology - Positive
- Technology - Negative
- Orientation - Positive
- Orientation - Negative
- Perception of independence and safety - Positive
- Perception of independence and safety - Negative
- Time - Positive
- Time - Negative

- References to difficulty or fear in certain spaces
- Infrequent use

Thematic analysis is a reflective process; this process is therefore repeated until satisfaction with output is attained. The dataset extracted from this analysis is included in Appendix Q and P, including participants' ratings for each environment and the results from coding participants' responses.

9.2. Understanding Behaviours in Different Environments – Results and Discussion

9.2.1. Overview of Results

Figure 9.1 summarises the average confidence scores of all participants in different environments. To aid readability, the environments are ordered from minimum to maximum average score for VIPs. It can be visually seen that the order of increasing confidence for VIPs does not correlate with that for NSPs. Moreover, a relatively lower-scoring environment for VIPs may be a higher scoring environment for NSPs, and vice versa; this is exemplified by the office/university building and stadium environments, respectively.

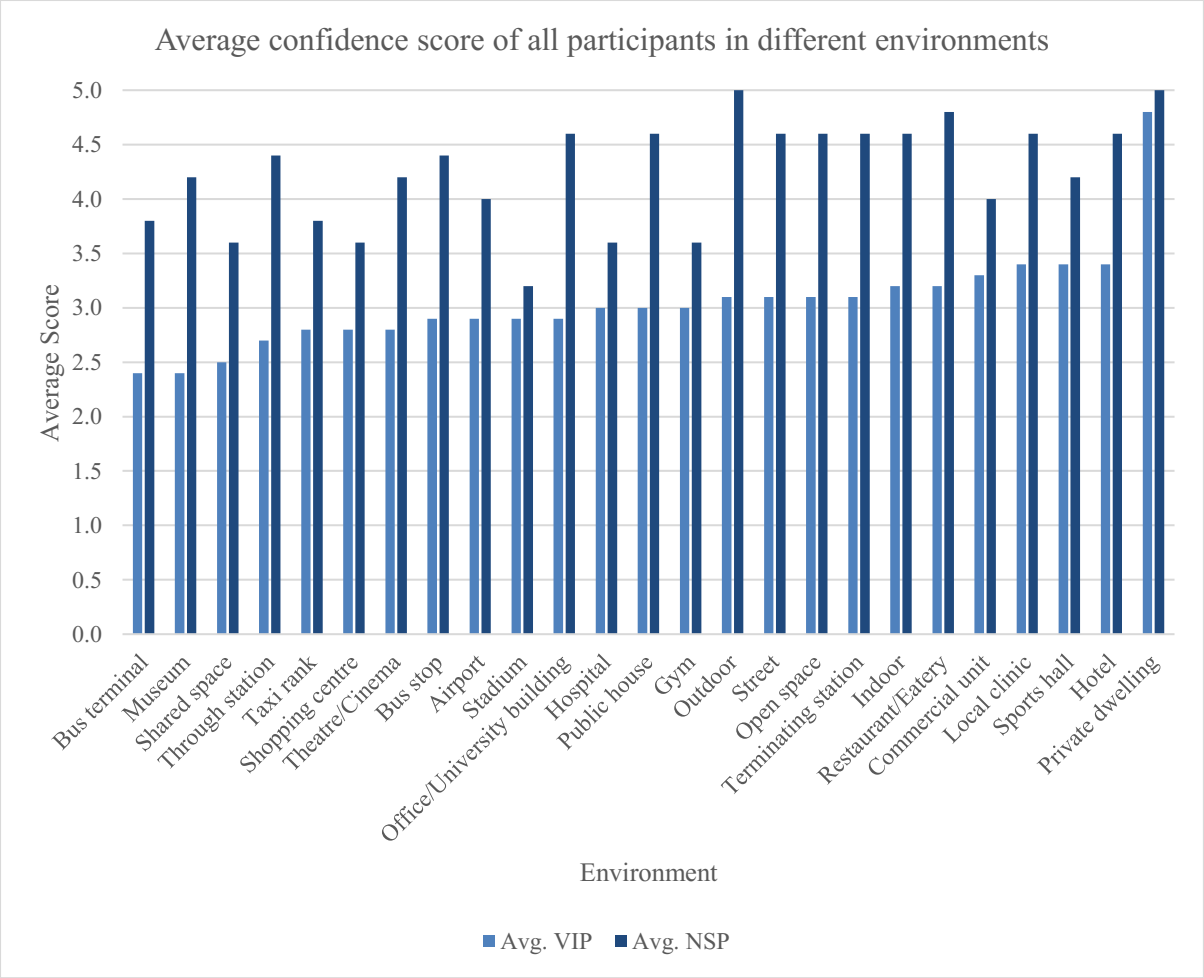


Figure 9.1: Average confidence score of all participants in different environments.

The average score for all VIPs is 3.0 (SD = 0.5, CV = 15.1%) while the average score for all NSPs is 4.2 (SD = 0.5, CV = 11.6%). The NSPs are therefore more likely to score higher in each environment, although their consistency is similar to that of VIPs. Private dwellings

presented the smallest disparity of 0.2 between the average VIP and NSP scoring of 4.8 and 5.0, respectively. The largest discrepancy between scores is 1.9 in the generic outdoor environment where average VIP and NSP scores are 3.1 and 5.0, respectively. To better distinguish scoring within the VIP groups (B, PVL, and CVL), Figure 9.2 plots the average scores of these VIP groups for each environment. The same environmental order of increasing average VIP score is maintained for comparison.

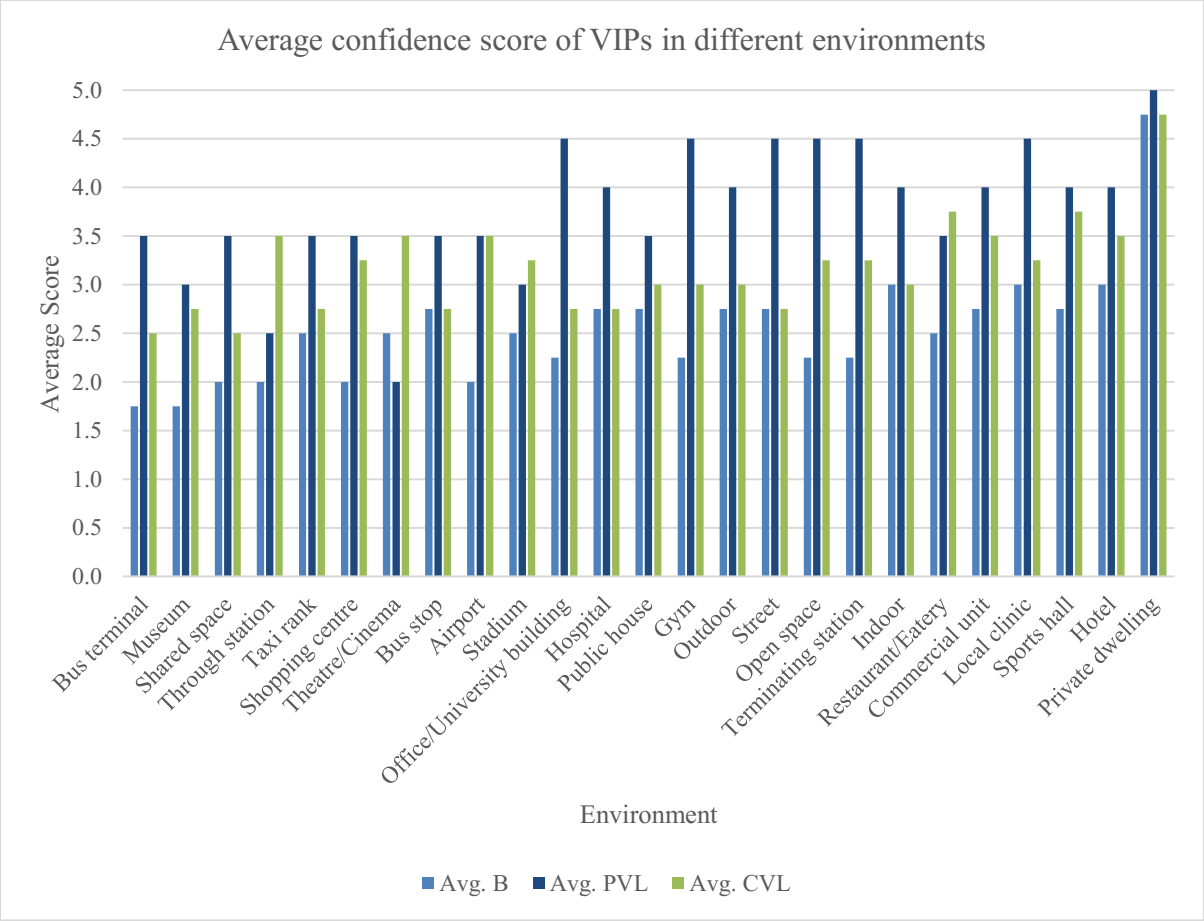


Figure 9.2: Average confidence score of VIPs in different environments.

All VIP groups present a general uptrend in average scoring as the aggregate average score increases. However, the scoring within groups is substantially different. The lowest scoring group, on average, is the B group at 2.5 (SD = 0.6, 23.5%), followed by the CVL group at 3.2 (SD = 0.5, CV = 15.5%), and the PVL group with the highest average score of 3.8 (SD = 0.7, CV = 18.3%). This is similar to the order of scoring in the walking experiments described in Chapter 8 and attributed to the PVL and CVL's improved visual function relative to the B group.

However, the small subgroup sizes (particularly for the PVL group) diminish the statistical significance of these results. Rather, observing the reasons for the discrepancies between VIPs, their subgroups, and NSPs provides an indication as to how challenges vary across environments per individual. The extensive interview and analysis of these discrepancies for each individual, as conducted, therefore greatly increases the validity of these results. The following analysis of each environment is ordered according to the environment's position within the interview structure, rather than in increasing VIP favourability, to reduce bias.

9.2.2. Outdoor

Table 9.2 includes participants' ratings and comments for an outdoor environment.

ID	C	Comments
V1	1	Recently blind means I am less confident. Blind brother has been blind for longer and is more confident. Don't trust not being able to see, and only trust myself. Do not want to take knocks or get lost, and will remember a knock forever. Brother doesn't mind taking knocks.
V2	4	Not afraid of it. I know my limitations. I don't rush too much when not sure and take my time and take care. Depends on whether area is familiar or not, but familiar makes a big difference.
V3	4	Recent surgery means I can see better at night and my confidence has improved drastically.
V4	4	In an outdoor space I have enough vision and awareness to stay safe.
V5	4	Depends on if ground is flat or has a lot of holes, and if it is familiar or not.
V6	3	Depends on whether I know the environment, and this is the main thing out of many. For instance, knowing where building works are and the chaos from cycle lanes.
V7	4	There's a lot of technology that I can and do use. I teach people that their most important aid is their voice: Ask for help. I am willing to ask and that is why I am confident.
V8	2	Depends on whether I know the area and have been there before. It is easier if I know the layout and difficult if I don't know the layout.
V9	2	All depends on whether I know the place or not. Somewhere new I find very difficult, and if someone invited me somewhere new, I might not even go and make an excuse.
V10	3	Confident if it is a known space (4) but less if it is unknown (3). In a known space I might not take my cane out.
N1	5	In some places I'm a 5 and in some I'm a 3, such as when navigating between cars and crossings. Generally, I am confident.
N2	5	I am usually good with directions, and I can find my way somewhere. In daytime it's alright without glasses (4) but in the evening it's worse (2).
N3	5	Use GPS and very easily relate to my position, location, and where I need to go. Happy to explore.
N4	5	Used to field trips and challenging terrain (going up and down).
N5	5	See everything I need to see to feel safe in that environment.

Table 9.2: Participants' ratings and comments for an outdoor environment.

Familiarity with the environment was generally the most prevalent contributor to confidence and perceptions of independence. Both participants with PVL particularly felt that their visual function was sufficient for navigating the outdoors safely, although no other visually impaired participants expressed positive sentiment towards visual function. Notable contrast in responses was observed between V1 and V3; V1's recent sight loss reduced confidence and willingness to take knocks or obstacles, whereas V3 expressed positive changes in sight following surgery to have improved their perception of confidence. Both V3 and N2 expressed that night-time lighting conditions impact visual function and confidence.

Following dependence on familiarity (6 VIP responses), positive perceptions of independence where the second most reoccurring theme (4 VIP and 2 NSP responses). Interestingly,

familiarity was not discussed by NSPs to play a role in their confidence. Obstacles had an impact on both VIPs and NSPs, with VIPs reporting knocks, building works and cycle lanes, and NSP reporting cars and crossings. Difficulty in certain spaces depending on familiarity or obstacles was specifically referenced by 2 B and 1 CVL participant, but no PVL or NSPs, suggesting that difficulty is associated with reducing visual function. Ground surface was noted by a B user (V5) to be a deterrent, specifically gradients and holes. Contrarily, N4 discussed how their adaption to these surfaces meant that they are confident in navigating challenging terrain.

9.2.3. Indoor

Table 9.3 includes participants' ratings and comments for an indoor environment.

ID	C	Comments
V1	1	The same as outdoors, but much more familiar in own home.
V2	5	Indoors is easier as I don't have to worry so much, and don't have much room to get lost. Feels safer.
V3	4	Same reasons as when I am outdoors as I find the outdoors and indoors to be similar after eye surgery. There are still some obstacles from time to time.
V4	4	Get around largely unaided if I have to. I don't consider that I need help to navigate, although there are places that I know are difficult.
V5	3	I am ok as long as I know the configuration, although steps are more difficult, and knowing if the ground is flat or sloped. It depends on good memory.
V6	3	Very confident around the home (4) but not if it's somewhere I've never been (2). I'll give the average of 3.
V7	3	Indoors is more difficult because of more obstacles.
V8	3	I feel slightly less danger indoors, no vehicles and such. I can also get more help indoors from people around.
V9	3	Would probably need someone to help guide me, to tell me if there are steps and obstacles. It's awkward visiting someone in their home because I can't help as much, so other people end up cleaning up and taking plates, I worry I might drop the plates.
V10	3	If it's one I know, I know where things are including steps, rooms, and so on, but if I don't know then I need to find out many things. Here, I go with the hope that at one point I will meet someone that will help me, but I still won't know if there are stairs and such, like in shopping centres or airports. In some areas, I can predict when there might be stairs, and I tell myself to go forward and not be fearful. I also factor in extra time to get lost and don't mind waiting, I don't want to be stressed for being late. It's the same issues indoors and outdoors, 'what is and what isn't known?', and you may sometimes not know who to ask.
N1	5	Most things are quite clear, and I never have issues locating something. I have good vision in the dark.
N2	5	As long as the place has good signage as to where everything is, it's easy to find stuff, but only with my glasses on. Without glasses, it would be a 3 indoors and I would have to ask people for directions assuming it's a place I've never been before.
N3	3	It sometimes feels easier to get lost as I don't have a map and there might be lots of corridors and floors. New places are harder. I like to use reference points, have a map, and know where I am.
N4	5	Same as outdoors, I'm used to going up and down stairs.
N5	5	Same as outdoors. Familiarity plays a role, but not enough to bring my score down.

Table 9.3: Participants' ratings and comments for an indoor environment.

In comparison to the outdoors, references to obstacles were more prevalent in VIP comments, and were mostly negative (3) with 1 VIP suggesting that there are fewer obstacles indoors. VIPs' references to sighted assistance or interaction with other people also rose significantly (4 references for indoors versus 1 for outdoors). An NSP with reduced ability to read signage also mentioned assistance, suggesting greater dependence on others indoors with reduced

visual function. There continues a connection between visual function and ability to perceive independence and safety.

Ground conditions were also more problematic indoors, particularly as steps were referenced 3 times indoors versus once outdoors by VIPs. Familiarity was referenced fewer times by VIPs (4 indoors versus 6 outdoors) but much more by NSPs (3 indoors versus none outdoors), particularly regarding corridors, signage, and disorientation. These are not dependant on visual function and suggest that indoor spaces, generally, require other means of mapping and orientation beyond sensory perception. PVL participants that demonstrated higher confidence than the remainder of the group in outdoor spaces made reference to obstacles and difficulty when navigating in certain indoor spaces, suggesting that this group experiences greater difficulty in indoor spaces.

9.2.4. Street

Table 9.4 includes participants' ratings and comments for streets.

ID	C	Comments
V1	1	Knocks, street furniture, and familiar versus unfamiliar streets make a big difference.
V2	4	Easier with the dog but still use sighted assistance where possible.
V3	5	Usually aren't many obstacles. Bollards, trip hazards, and other obstacles are well lit.
V4	4	No trouble, but I am aware I don't spot everything that I could. People can come out of my blind spot, and I end up bumping into them.
V5	4	Depends on whether there is a road crossing, people all over the place, kids with pushbikes, and the width of the pavement.
V6	2	Even if it's a street I know, there is so much that can be put on a street, wheelie bins, restaurant boards, bicycles. Obstacles are the main problems, and steps. I fell down steps in December, but this hasn't really stopped me from going out. I know what to avoid and take it as a learning experience. An issue is that the tactile textures at the top of stairs is different in different boroughs, same for flights of steps and bicycle lane crossings in different borough.
V7	4	Nowadays tech options are great on our smartphones so, depending where I am, I decide on which app to use. I ask for help and, depending on purpose, I plan ahead. Put me anywhere in Central London to the city and I will know my way through either tech, asking people, or landmarks I know. In foreign countries, I must plan ahead.
V8	2	I don't know streets well, what's around, and if there's any obstacles and street furniture. I will probably ask someone for help.
V9	2	Kerbs, steps, and raised pavements are challenging, as are lots of stuff that get left on streets like bags of rubbish, bicycles, and e-scooters.
V10	3	All depends on the known and unknown, like where obstacles are. I learn them by heart, where the bin is, the curb, the lights, even the sequences of light. A known street would be a 5 but, in an unknown, I'd be slower, take my cane, and wait longer at crossroads, so I'd go to a 3. There are days where people act or drive crazily, such as during football matches or red light jumpers. When I feel this, I hesitate and feel the atmosphere of the crowd. It makes me avoid places or take a taxi, same in bad weather.
N1	5	I have Google Maps and know exactly where I am going. However, a mix of cycling lanes being close to pedestrians and crowded streets can be problematic.
N2	4	The familiarity of a street definitely matters, and if I am somewhere new, I'd need signage. I can still navigate an unfamiliar area with Google Maps.
N3	5	No reason, I feel confident.
N4	4	It would take slightly longer if trying to map my way there. It's better If it's free of people.
N5	5	I feel like I can see the information that I need to be in that space.

Table 9.4: Participants' ratings and comments for streets.

Obstacles were the most prevalent topic for VIPs (referenced in 7 VIP responses), although V3 (PVL) was unique in their positivity towards obstacles on streets in that there are fewer and are usually well-lit. Likewise, V4 (PVL) did not reference street-specific obstacles, but that visual function limits their ability to detect people (acting as dynamic obstacles). Ground conditions were also prevalent, appearing in 3 responses, particularly curbs, steps, raised pavements, and

pavement width. Street furniture, bins, e-scooters, crossings, and cycle-lanes were other negatively perceived obstacles.

Interestingly, dependence on familiarity only appeared in 2 VIP responses, perhaps given that street obstacles are dynamic, even in familiar streets, as referenced by V6. Contrastingly, V10 references learning the position of obstacles and landmarks including the sequence of light, showing variability in the usefulness of obstacles. Negative impacts of congestion appeared in 2 VIP and 2 NSP responses. Positive perceptions of independence and safety only appeared in PVL and CVL responses, but not in B responses, suggesting that visual function has a role in detecting the dynamic obstacles on street that memory and familiarity could not account for.

Positive sentiment to technology and the ability to orientate appeared in 2 NSP responses, but only 1 VIP response, perhaps suggesting that orientation through technology is not a priority for VIP users. To support this, 3 VIPs referred to human assistance, 2 being B. V2 states that their guide dog is useful, but that human assistance was more valuable. 2 VIPs, both with CVL, mentioned the use of time to assist with moving safely and independently, whereas 1 NSP negatively mentioned the additional time required to navigate. 2 VIPs conveyed positive sentiment towards orientation while 1 VIP conveyed a negative sentiment, in total appearing less than obstacles, concluding that obstacles (including those that are dynamic from crowd behaviour) were the primary factor affecting confidence for VIPs on streets.

9.2.5. Open space

Table 9.5 includes participants' ratings and comments for open spaces.

ID	C	Comments
V1	1	Same as street. Not wanting to bump into anything or get lost.
V2	2	Not so confident. Easier to get lost because you turn around a few times and then get disorientated.
V3	4	Have to walk through a park on my walk home, and there are sometimes no lamps in parks, and so I can struggle to see if there is someone on a bench.
V4	5	If I have to get to a particular place, then these may be challenging, but I have no issue in just moving around these spaces. For instance, I can see hedge lines but would not know if there is a fence blocking my route.
V5	3	There can be rocks and holes on a beach. It is also difficult because there are no boundaries.
V6	3	If it's a park with pathways, then I'm more confident but still have to be mindful of steps (3). If it's a promenade and level, then I'm even more confident (4). Texture matters, so sandy or pebbled beaches are worse (2).
V7	3	If it's not familiar, it will be a 3. Parks are one of the few places in the world where I can daydream and not have to focus on every step or cane swipe. I might not be able to know exactly where I am, but technology can help me. If I'm there for a while it would go from a 3 to a 4.
V8	3	Bit more confident as they're wider areas, so I don't expect as many obstacles.
V9	4	Better than a street as I don't feel that there's always going to be a step where I might fall. I can generally navigate them on my own but, if I go with people, I let them walk first to avoid the steps and my fear of falling.
V10	3	I slow down and won't just run freely. I would first map it out and find where the holes are, especially if there is no proper path. I will be more confident if there is someone with me.
N1	5	No issues at all, but it may get dark in some parks so it's more of a safety concern.
N2	5	I can and am happy to wander around as they are open and there is no boundary.
N3	4	When it's not manmade it tends to be less organised. I like organised places.
N4	5	I like the park and the beach.
N5	4	The constraints are different to a street, I don't know what I will come across.

Table 9.5: Participants' ratings and comments for open spaces.

Open spaces drew difference in the responses given by participants relative to more confined outdoor spaces such as streets. This is reflected by references to boundaries which appeared in 5 VIP responses, 4 being negative. Similarly, orientation was equally referenced with 4 occasions being negative. These appeared for all VIP groups. Interestingly, a B participant discussed the wider boundaries of open spaces to be positive because of a reduced anticipation of obstacles. Ground surfaces appeared to be slightly more prevalent than obstacles in 4 versus 3 VIP responses, primarily with negative sentiment regarding steps, holes, and uneven surfaces in areas including parks and beaches.

Both PVL participants referenced use of their visual function to orientate, demonstrating shortcomings in this in open spaces because of poor lighting or being unable to detect the boundary. Indeed, lighting issues appeared in an NSP response but was more pertinent to safety rather than orientation or obstacle detection. Similarly to streets, 2 CVL participants expressed a desire to use time to positively improve their safety and mobility within open spaces. NSPs showed a generally more positive response to the wider boundary, with only N3 stating less

satisfaction with the organisation of natural areas versus manmade areas like streets. Mentions of technology are also reduced versus streets (3 in streets versus 1 in open spaces). Likewise, there was no mention of congestion in any responses, indicating that there are some benefits of open spaces to mobility, but that wider boundaries can be disorientating, and that participants have not explicitly described technology to positively aid this.

9.2.6. Shared space

Table 9.6 includes participants' ratings and comments for shared spaces.

ID	C	Comments
V1	1	Traffic would make me even more scared, especially big lorries and trucks. I can't tell how far away things are like a loud lorry or truck. A lorry backed into me once as I didn't know beeping sound was reversing, and now this sound is even scarier as I know what it means. Felt angry and traumatised, and this is made worse with recent hearing loss.
V2	3	Can be a bit confusing, congested, and dangerous, and so one has to be more careful.
V3	4	Can follow people and there are typically many people here, and so I feel more comfortable following them.
V4	3	Don't like them. They have poor colour contrast, I end up walking into one of the bollards, and I don't know where cars will stop.
V5	3	Crossing the road is a problem because of cars and obstacles, especially cars going quickly.
V6	2	Cycle lanes and pavement are a high collision risk. Bus stop bypasses are difficult as cyclists don't know about crossings, I don't think visually impaired people were involved in this consultation.
V7	4	It is a challenge, especially not knowing where the edge is. It's a 4 for exhibition road because I know it, but a typical shared space is between a 3 and 4. If I am told or know it's a shared space, I'd walk away from the road.
V8	1	Lots of people and items on street so they're difficult to navigate.
V9	2	Really don't like these, and not knowing where you're meant to stand and how to cross because people don't stop for you.
V10	2	I will take out my cane and listen carefully as I don't know the limits of my safe space. I wouldn't know which way traffic is coming from, especially traffic that makes no noise. I can't walk down the street looking behind my back, and I don't look blind. For instance, I might look straight at a car, and they would think that I saw them when I actually did not. In shared spaces, I feel that I am expected to get out of the way, and the cars bully everyone.
N1	4	Lots of confusion between traffic and walkways. More of a safety concern of when to cross and not being able to identify the street or pathway.
N2	3	I don't like that I have to trust the driver when I cross the road, and that crossings are not always visible. I do not want to put my trust in the driver stopping for me as I cross. I know it is hard to spot obstacles as a driver.
N3	4	Too many people causing congestion.
N4	3	I have to dodge in and out of people, I don't like the crowds. I move quite quickly but then have to slow right down.
N5	4	These can be a bit unhelpful, it's still very unclear where the pavements are versus the roads. I think I'm going to get run over most of the time.

Table 9.6: Participants' ratings and comments for shared spaces.

Shared spaces were, on average, ranked as the worst outdoor environment by VIPs and NSPs. Interestingly, the effect of familiarity was minimal here, and was only referenced by 2 VIPs. Negative perceptions to obstacles were the most reoccurring theme in responses, with 8 VIPs and 4 NSPs mentioning this. The primary obstacles were vehicular traffic and pedestrian congestion, and these prevailed for all experimental participants regardless of impairment. This was closely correlated to negative sentiment to boundaries, referenced by 5 VIPs and 3 NSPs,

suggesting that limited delineation in shared spaces between the user and dynamic obstacles is the primary pain point. The dynamic nature of these spaces also explains the reduced dependence on familiarity as the positive use of obstacles for landmarking, as was done by V10, was not present in these spaces.

This was also linked to negative feelings of independence, safety, and orientation in that 4 VIPs referenced confusion in orientation resulting from not being able to identify crossings and safe pathways. For V1, degrading hearing and the resulting reduction in vehicle detection added to their fear of these environments. This is unlike open spaces or streets, and it appears that the pain points in shared spaces are exacerbated by visual impairment, rather than being driven by them, as people with visual impairments specified very similar sentiment to those without.

Finally, it is noted that V3 and V4 with PVL continue to reference some dependence on visual function within their responses, particularly that V3 uses their sight to visually couple with and follow people around them. Such behaviour was identified in the previously discussed group dynamics experiment, reiterating a positive effect of crowds in that their motion may aid the orientation of partially sighted individuals in complex spaces.

9.2.7. Bus stop

Table 9.7 includes participants' ratings and comments for bus stops.

ID	C	Comments
V1	4	I usually ask for help and am confident, and can ask the driver when hearing the bus arriving. I am now not sure when a bus is coming because I can't hear it and am therefore less confident. This is a new thing to get used to and quiet buses are a problem. The driver must know to help blind passengers.
V2	3	Hazardous. I still have to rely on someone being there and, if not, have to rely on the bus stopping for me. There could be more than one bus around, or none at all. Drivers sometimes don't give clear answers, or don't give answers at all. There should be audio at bus stops saying bus numbers and when they are approaching. Locating a stop can be confusing, especially if it's a new route or stops get moved. People parking cars on the stop can be very troublesome and this occurs at my local stop.
V3	4	Bus stops usually have lights and are well-lit, but I cannot give them a 5 because I struggle to read signs at the stop, although I have no issue identifying the approaching bus.
V4	3	When looking for the bus coming, I struggle to see the bus number and, on occasion, it will drive past because I didn't realise in time. Focusing on a moving target is hard. It makes me uncomfortable because I might upset someone by wasting their time if I hail the wrong bus.
V5	3	Depends on how many buses are at the stop. It is easy if it is not busy, and crowding makes it difficult when buses all come in one go, especially buses at the back. 'Is it the 2nd or 3rd bus?' and this is difficult even with apps as buses don't always stop in London. I need to know where the bus is. The sign also needs to be at eye level.
V6	2	Quite hard to identify buses. Even with magnification software it is hard to focus on the moving bus. A problem is when many busses stop at once and I can't tell where each is, especially when overtaking each other. Talking to the bus driver is harder because of the new COVID screens.
V7	4	Great in London because of tech. Before apps, I would stop every bus and ask for the number. Now I know which are coming and, if there's more than one due, I would stop them both. I'm generally good with buses.
V8	1	Finding bus stops can be difficult and I may need help. The main problem is when 2 or 3 buses come and I have to ask for their numbers, especially when the bus I need is behind another. The main objective is to find my bus and, if I can't find it, then I can't fulfil my objective. 98% of the time it works out though, and I'll just have to get help from someone.
V9	3	Have to use monocular to see the number coming. The lighting on bus number blinds isn't very good depending on the time of day, like the evening when they're not yet lit up. I can't see the orange lighting on the bus timetable. Some stops even have screens at the shelter and those are very useless, I can't see them because of the lighting. Floating bus stops are also very hazardous.
V10	2	I can't see the bus coming and only see it at the last moment. I wave for anything big and red, and it's not always a bus. I always ask the bus driver for the number and where they are going, and they don't always speak up. I don't know if they're going to be polite or fed-up, so I am always a bit anxious when asking. If the first bus wasn't the right one but the second one was, I would've missed the second

		one by the time I went to check. Announcements have made bus rides far more comfortable.
N1	4	Sometimes, buses might stop in front of each other, and they won't see you.
N2	4	I like bus stops with screens that explain when a bus is arriving, but use my phone when not available, although I don't like using my phone because of theft potential. I can still identify the bus without glasses but only when it comes close.
N3	5	Specifically in London, I'm well informed as the live transport updates are good.
N4	4	I'm completely happy to do so and catch buses frequently. The issue is If I can't quite see the bus stop or where the next stop is.
N5	5	I generally don't have an issue here; my main concern is safety.

Table 9.7: Participants' ratings and comments for bus stops.

Given that there is a more focused task-set at a bus stop versus navigating other open spaces, the range of responses was significantly different in this space than for others such as streets and shared spaces. 'The main objective is to find my bus', as stated by V8. Of the most prevalent issues was congestion at bus stops where several buses stop behind each other or overtake each other. This predominantly affected all 4 B participants, and was referenced by one with CVL when visual function was not sufficient to detect the bus coming in time.

The theme of sighted assistance, particularly for bus drivers, was also referenced on 8 occasions, with 5 being negative and for different reasons. V1 describes that onset hearing loss has reduced their ability to hear and stop buses approaching, but that drivers should know to do this, especially with quiet electric buses. V2 explains that drivers may be unhelpful in providing clear answers, while V6 expresses communication difficulty with COVID screens in place. Notably, V4 considers the driver and passengers' perspective and is conscious of wasting their time. This is similar to V10's response in that self and social awareness of others limits confidence within bus stops. It can be concluded that human assistance in bus stops is strongly correlated with not being able to identify the approaching bus, and that this is not always guaranteed, especially with several buses approaching.

A negative time-based sentiment was also introduced within the responses of participants with some remaining sight (2 CVL and 1 PVL) in that they would use their remaining sight to identify the bus as it approaches, but that this may not allow them sufficient time to hail the bus. N2 also described this sentiment when not wearing their glasses. N4 expanded on this by describing their inability to detect certain stops. This mechanic was not referenced by B participants, further reaffirming a correlation between the use of visual function and negative time sentiment when using buses. On visual function, signage was referenced on 4 occasions by VIPs as not being sufficiently positioned and visible to identify stops and buses. On one occasion, this was attributed to time of day by V9 when the bus blind is not lit up.

Ultimately, these challenges led to difficulty for 5 VIPs and 1 NSP in certain conditions; however, the remainder express adaptations to overcome these, such as hailing all buses that come by, or the use of technology. 2 NSPs but only 1 VIP expressed positive use of technology, in particular live transport updates; however, 3 VIPs yielded negative sentiment to technology. On two occasions, this was that magnification tools could not detect a moving bus, while the other referred to inaccessible timetable screens at stops.

9.2.8. Bus terminal

Table 9.8 includes participants' ratings and comments for bus terminals.

ID	C	Comments
V1	3	Surrounding noise is worse and it feels like I'm in the middle of nowhere. Bus stops feel distinct with clear boundaries, but terminals have no clear boundaries to me.
V2	1	A nightmare. I could not do it alone and sighted assistance is needed, so I will always seek sighted assistance. There are so many different coaches, and some are in the middle of open spaces, and even sighted assistants don't always know where to go. Finding the correct terminal is therefore hazardous and very archaic.
V3	4	Haven't used a bus terminal before but will likely feel like I am in a train station with which I am comfortable.
V4	3	Struggle to tune in to the signage. When you have familiar seating, parameters, and boundaries, you know where to look for signs and what to read. However, in unfamiliar environments, I don't know where to look for signs. Colour plays a role in this and it's the same for airports and train stations. Locating the sign can therefore be the challenge, and then there is also the challenge of 'is it readable?' If I'm with someone I rely on them and trust the other person, especially when under time pressure.
V5	2	Bus terminals are too big and it's only possible If I find help.
V6	3	Once I know the stops and what vehicles go there, that's easy. They have to stop there and there's enough people about to tell you what's coming. This isn't the case at bus stops. Like an airport, once you know the gate number, it's much easier and you can just quickly ask someone for help.
V7	3	I know I'm going to have to ask for help, either for the bus stand or to get me to a staff member if I don't know which one.
V8	1	Definitely would need help here as I wouldn't be able to find my way around on my own.
V9	2	I sometimes cannot find signs because they are placed too high, and it's hard to find the bus that I am looking for. I therefore try to avoid them. There is no pattern to work out how they work and how to best use them.
V10	2	Worse than a bus stop. All the stop signs are very high, so I cannot see them. I wish they had bigger numbers lower down. Displays are too chopped up to be read with a monocular or binoculars. People usually know where they need to go and I may ask them for help if I need to, and so I have my white cane out to let people know.
N1	5	All bus stops are clearly labelled and well organised. It's an all-in-one area so I have good navigation within it.
N2	4	Signage is very important. My first time in Victoria was not too hard because it was well signposted. It's usually well-lit with big enough signage, but there's always confusion in being in a place for the first time.
N3	3	I don't use them. There's too many people and they're not so well organised. Information may not be readily available.
N4	3	They're more likely to be busy.
N5	4	They can be quite confusing spaces due to signage. There is little signage and I often think from a tourist's perspective. I struggle to select which stop I need to be at without an app.

Table 9.8: Participants' ratings and comments for bus terminals.

Even though the task of catching the right bus in the bus terminal is a similar objective to that in a bus stop, the execution appears to be different, and this is that there is substantial orientation required for the user to find their bus. Indeed, orientation challenges were referenced by 7 VIPs, including all 4 B participants. This can be attributed primarily to the large space within the bus terminal relative to bus stops, causing negative sentiment to boundaries (3 VIP), signage (3 VIP), congestion (1 VIP), and visual reference (1 VIP). Only 2 VIPs and 1 NSP referenced familiarity as a contributing factor, thus suggesting that the shortcomings within these spaces may not be accounted for through cognitive mapping. A similar issue was found in shared spaces. In contrast, however, the issues in bus terminals revolved predominantly around orientation rather than obstacle avoidance or ground condition which were, perhaps surprisingly, not referenced at all in bus terminals. V9 affirms this by stating 'there is no pattern to work out how they work and how to best use them.'

As a result, human assistance was referenced by 7 VIPs as being a critical part of their use of bus terminals for orientation, and this therefore hindered independence, as stated by 6 VIPs, and caused infrequent use, as referred by 2 VIPs. Notably, visual aspects including signage and colour only hindered CVL or PVL VIPs (4 responses), whereas boundaries were the prevailing challenge for B VIPs (3 responses). The contrast between certain VIP and NSP responses was unexpected given their direct contradictions. For instance, V1 and V2 refer to feelings of being in the middle of nowhere, no clear boundaries, archaic, and hazardous. Contrarily, N1 states clear labelling and organisation within bus terminals. Signage appears as the most prevalent tool (positive and negative) for NSPs' orientation, chiming with the CVL and PVL group.

9.2.9. Taxi rank

Table 9.9 includes participants' ratings and comments for taxi ranks.

ID	C	Comments
V1	3	I am not sure how they work. Drivers don't oblige you all the time and neither do other people in the queue. Not sure if drivers will come to me, and they may be rude and don't want to take me because of the extra hassle.
V2	3	They're alright, but more of them is needed. I need to know where they are and if someone, or a taxi, is there. Having them located closer to a station makes a good difference as I sometimes have to cross a busy road from the station.
V3	3	Sometimes struggle to see and identify the taxi that I need.
V4	4	Very rarely use a taxi as I don't usually think of getting a taxi and prefer to cycle or take the bus.
V5	3	Easier than the bus terminals as I can talk to the driver.
V6	2	Quite difficult. Don't know the layout and, if I'm getting a taxi, it's usually because I'm somewhere I don't know. Ranks have barriers and poles, and these are unfamiliar. I also don't know which driver I'm talking to.
V7	3	Finding the taxi rank or bus stop can be the challenge, but apps have helped with this. Taxi ranks are worse than bus stops for this, and this is why it is a 3. If I knew where the rank was, it would be a 4. If I'm behind or in front of someone, then people are typically very helpful. You have to help them to help you.
V8	1	The station staff usually take me to the nearby taxi rank because I usually need help with them.
V9	2	Not too bad and fairly straightforward because you find the queue and then join the queue, I follow the crowd. The problem is that hailing taxis can be hit and miss. Some may come with lights on, but it can be hard to tell which is free. Fast turnovers mean that four taxis may be pulling up, and I feel a bit on edge as I'm not sure what it's going to be like at the end of the queue.
V10	4	I can't see if there is someone in the car, and have tapped the window when someone was already in. The queue helps and the rank is a contained environment. I'd hate it if the rank was in the middle of the road.
N1	4	There's very little space for someone to stop for you, so they tend to have to stop on the road.
N2	4	I don't usually visit them but, when I do, it's confusing. I couldn't tell what drivers were saying and what the light on or off means, 'Is the taxi taken?'.
N3	3	I'm not used to them.
N4	3	Very rarely use taxis. I wouldn't mind but I don't have much experience.
N5	5	Safety remains the biggest concern.

Table 9.9: Participants' ratings and comments for taxi ranks.

Results for taxi ranks were mixed and it appears that a multitude of factors affect the usefulness of taxi ranks with similar frequency across groups. The most prevalent theme was references to difficulty under certain conditions when using a taxi rank (5 VIPs and 1 NSP). Responses from 2 CVL and 1 PVL participant attributed this to visually identifying if a taxi is taken. An understanding of the taxi's lightning system and visually identifying if a passenger is present were primary contributors to this in these participants' responses. For the B group, sighted assistance prevailed as the prominent factor, but was mixed between positive and negative sentiment; V1 described that taxi drivers may be rude, but V5 described that being able to speak to the driver improved their confidence. V8 introduced station staff as usually assisting them to use taxi ranks. As seen in bus stops, a different mechanism of environmental operation was

therefore identified between users with and without sight, where those with sight would prioritise visual reference, and those without would prioritise sighted assistance.

Obstacles, including bollards and crossings (2 VIP and 1 NSP response), and the subsequent positioning of taxi ranks negatively attributed to orientation and perceptions of safety (2 VIP responses). Interestingly, congestion in queues at taxi ranks was found to positively improve the experience of two CVL participants in that the queue allowed them to follow the crowd and orientate themselves. Although a CVL respondent further explained that this leads to faster turnovers, greater time pressure, and feelings of being on edge. Finally, infrequent use of taxi ranks was prevalent across 3 NSPs and only 1 VIP. This may suggest a greater tendency for VIPs to prefer using taxis for transport.

9.2.10. Through station

Table 9.10 includes participants' ratings and comments for through stations.

ID	C	Comments
V1	1	1 in unfamiliar and 3 in familiar. It is all too much unless I know the station. In a familiar station, I know where the wall is, boundaries, and where to ask for help. In an unfamiliar station, I would ask for help and the experience would be completely different because I do not know how wide the platform is. I am very scared of walking onto the track, especially tapered edges. I do not want to experiment, and I like knowing the dimensions of my space.
V2	3	Fine, but a sighted guide is needed and always sought, especially in larger stations like Clapham junction. Need sighted assistance to get on steps between trains and platform as this is dangerous and I could fall. I need to put my hand on the handle inside the train door before stepping up, even with my guide dog which fell between the gap twice.
V3	3	Struggle to identify where I need to go and where to cross onto the next platform and find the next train. I am happy to walk but only if I know where I am going.
V4	2	Had to once get a train from King's Cross to Watford where I had instructions on where to go, but the platform was in a different building, and I couldn't see the sign to get to that building. I had no cues as to where that was and it was very disorientating, so I almost missed the train. It is generally disorientating, but I will try to do things independently until I fail. To a degree, it's humiliating to ask for help from a staff member.
V5	2	I'm alright in a familiar station, but it's hard in a crowded and unfamiliar station. It also depends on how unexpected the change-over is. Liverpool Street, Green Park, and King's Cross station are hard to navigate, they're too spacious.
V6	4	I've been using the tube for a very long (since I was 8), and went to school on my own on the tube. There are very good announcements, and these are important, so I'm quite confident. Stations with several trains are more difficult, and some don't announce destination on the platform, only on the train. It doesn't give me time to work out if this is the right train. I can't rely on announcements at terminating stations too much as they announce train and platform information too close to when the train is departing.
V7	3	If it's in London or the UK where I can ask for assistance, then it's a 3. If I was getting off a train and can't find assistance, then I know where the front of the train is and would ask for help, or I'd walk around until I find someone.
V8	2	If I know the route, then it's fine and I might do it without help. It's alright for the majority of the time because I have a routine, but if I am going to a new place like attending this experiment, then I would need help.
V9	2	These can be very difficult, especially large stations with tunnels to different platforms and trying to see the numbers. It's harder when people are rushing along as you get in their way as you get closer to see the signage. Finsbury Park, Clapham Junction, and Stratford are particular examples. Swapped escalators also make things harder as I can't tell their direction if people are not on them.
V10	5	Some stations change their colours, such as ads, and these can make me doubt myself, I'd be unsure if I was in the right station or place. Escalators changing directions is scary. I usually travel independently and only ask for help in a new station. I've been using the underground since 1985 but, in a new town or network, I would keep asking until I know the route.

N1	5	Everything is well labelled and clear. Sometimes it says that the train is approaching but the train doesn't come. So the Issue is the accuracy of information rather than accessing it. Same for buses, some may come, or even two at a time.
N2	5	It's much easier now that I know what all the station terminology means, like eastbound or southbound, but it was harder initially. They provide signs that are very clear, and I can follow people.
N3	4	Sometimes it takes longer than expected to get to a platform.
N4	4	You always have a few people around you and have to therefore keep your eyes open to deal with people and follow signs.
N5	4	Depending on where you are in the station, you may not know where you are going. Limited signs and lots of people make it worse.

Table 9.10: Participants' ratings and comments for through stations.

Orientation issues (9 responses) were the most prevalent causal factors of difficulty when using through stations for VIPs (another 9 responses), particularly in understanding boundaries and locations of trains and platforms. All VIPs were therefore affected by this regardless of visual function, but the coping mechanisms employed by each appear to be different. Sighted assistance was positively referenced by 3 B and 2 CVL participants, but none within the PVL group. Notably, a participant with PVL expressed that it was 'humiliating' to ask a staff member for help given that they are accustomed to trying to operate independently and using signage, although this was also negatively referenced. Indeed, similarly to bus terminals, it appears that the group with the better visual function are less positively inclined to sighted assistance.

The effect of familiarity appeared in 5 responses, and this pertained to orientation, understanding the positions of obstacles (particularly platform widths), and the size of stations (bigger boundaries). Congestion had a predominantly negative perception by VIPs and NSPs (4 responses), although it was interesting to note that a participant with CVL utilised the visual reference of people standing on escalators to detect the direction of the escalator, and that reduced congesting would lead to difficulty in doing so. Similarly to other transport infrastructure, negative references to time appeared in the responses of 2 VIPs and an NSP, and this related to time pressure when finding the transport vehicle, or insufficient temporal information to determine the vehicle's departure or arrival time. NSP responses considering information acquisition only referenced the accuracy or availability of information, rather than its accessibility (4 responses), whereas VIP responses predominantly discussed the accessibility of information rather than its accuracy (4 responses).

9.2.11. Terminating station

Table 9.11 includes participants' ratings and comments for terminating stations.

ID	C	Comments
V1	1	1 in unfamiliar and 3 in familiar, the same as a through-station. Familiar stations are much better because unfamiliar stations have the same dangers, and I also wonder if anyone can see me to help me.
V2	4	Always have a sighted assistant to meet me when getting off a train, and these are typically ok, although I can find my way out on my own in my local station. Station staff are key, and every station should be manned, although some are not.
V3	5	The way out signs are usually well-lit and yellow, and I can easily leave. I follow people and so the exit is obvious.
V4	4	Usually finding an exit is easy, but not always the right exit. A lot of natural signage is from platform entry to the station's exit.
V5	2	Bad if you don't know the exit. This could be a 5 if it's a familiar exit. I usually try to get my bearings, and this is easier outside.
V6	3	Depends on its familiarity and size. I find the exit myself in small stations, but I usually ask for help at larger stations like Reading station.
V7	4	I'd walk from the front to the back until I find an exit, but I know that I will eventually find my way out so that's ok.
V8	2	Same as for a through-station. If I've done it two or three times then I might be able to do it on my own, and if I get stuck, I ask for help either from passengers or by booking in advance.
V9	3	Same as through-stations, including signage, lighting, and congestion. 'Is it possible to follow the people out?'. Where I get off the train, there are sometimes other things hanging down from the ceiling, and these block the exit signs.
V10	3	Several exits and train-underground intersections make things complicated. I don't know which exit I need and, if I wasn't given a name, it can be exhausting. I sometimes end up going backwards and forwards along corridors.
N1	5	Exits are always clear.
N2	5	Easy when you follow people, same as with through-stations. I don't like that it can take some time to locate the way out because there are lots of signs, but I will find my way eventually.
N3	5	I'm usually fine when exiting.
N4	4	Same reasons as in any station, there's lots of people and so on.
N5	4	In my home station, I'm a 5, but the issues in other stations are the same as those in through stations.

Table 9.11: Participants' ratings and comments for terminating stations.

As expected, there were similarities in the responses of all participants in through and terminating stations, particularly in that familiarity was the most prevalent theme in both settings (included in 6 responses across each setting). However, it appears that the severity of issues in terminating stations are of lower magnitude than in through stations; terminating stations were rated, on average, significantly more highly than through stations by VIPs (2.7 versus 3.1). Interestingly, the average rating by NSPs was 4.6 in terminating stations, a 0.1 reduction than in through stations. The increase in VIP performance was attributed to improved orientation performance (4 positive and 4 negative responses) versus only 4 negative responses in through stations. Moreover, there was no mention of obstacles or ground surfaces in exit stations, perhaps given that users would primarily interact with exits rather than active platforms in these scenarios, thus presenting smaller risk.

A theme across responses was that the participant would eventually find an exit and would use human assistance if not (referenced positively in 4 responses). Furthermore, participants with partial sight identified a good ability to detect exit signage which is often differently coloured and illuminated in comparison to other signage at train and underground stations. Such can be explicitly found in the responses of both participants with PVL. Time in either a negative or positive frame was not referenced in terminating stations as there is no longer a train to catch. An overall change in task is therefore present in terminating stations, and one that appears easier than locating and boarding transport vehicles. To support this overall finding, references to difficulty or fear in certain scenarios reduced from 10 total responses in through stations to 5 in terminating stations.

9.2.12. Airport

Table 9.12 includes participants' ratings and comments for airports.

ID	C	Comments
V1	1	Can't tell anything as it feels like an open space with no boundaries, so I will always need help. Never been there alone as I would never be able to go in a particular direction. Crowds are disorientating and make me lose track. It worries me.
V2	1	Assistance makes a significant difference (3 with assistance, 1 without). I need help as it is impossible to navigate airports on my own, and I've only travelled with help, but still feel happier at airports than train stations because there are no platforms to fall from and I don't have to worry about getting on a train. It is a matter of finding the right terminal and I just need help navigating there. I don't fly much but it has usually been good, although I might need to wait for help.
V3	3	Identifying the check-in desk is a struggle, but I can travel through them independently.
V4	4	I can go around independently looking for an information screen that I can read.
V5	4	I always get help at an airport. The first thing is to be able to find the check-in desk, and here I find someone to guide me. I ask people and it's usually alright, but have to go early due to congestion.
V6	3	If I end up somewhere I shouldn't be, there is always someone that will point me in the right direction. However, getting help is not easy from the start because I get told to sit down and wait for someone to come. Some foreign airports do not understand disability and ask you to sit in a wheelchair or in an office, and this is very inconvenient. I travel with my visually impaired wife we may get separated or lost, and so I arrange in advance so we don't panic when it happens. There are language and cultural barriers in foreign airports.
V7	4	Aira (smartphone sighted agent app) have been adding airports to their app and they're free to use here. I'm tempted to use airports as I know that I'm going to get the help I need.
V8	2	I can get help typically from the taxi driver to the airport entrance. The difficulty is that airports are a big wide-open place and so I will need someone to help me find the check-in desk. Somebody needs to help me near the entrance. Finding someone is the initial challenge but after this it is like a domino effect, and I am directed to all the people I need. I might even need to ask a passenger initially for this to happen.
V9	3	International airports like New York are very helpful. The staff will help you and lead you, whereas in the UK, it is difficult to find where you are going. People might point in the right direction but don't take you there. Trying to tell escalator directions without people on them is still hard here.
V10	4	I usually go from staff to staff, from check-in to passport control to the terminal. I tend not to use the disability support because I want the freedom to go to the duty-free and browse around, so I usually go much in advance and plan ahead. Once, I got put on the wrong plane. I sometimes take a ferry and need help to find the cabin as I'm never sure that I'd see the numbers on the displays because of colour contrast, size, or lighting.
N1	5	All is clear with good signage.
N2	3	If it's a new airport and I don't have glasses, I can't see the screens easily and so it takes me a while to figure out where to go. I'm definitely less confident in an airport than in a tube station, especially as people are going everywhere in an

		airport. The first couple of steps are hard because there's no logical flow but, after security, finding the gate is easier. Multiple floors make things more confusing.
N3	5	I do like them because they're mostly well-organised and you can find your way through them. Everything is pointed out for you.
N4	3	There is a lot more to look for and, quite often, you are waiting for a gate number. Sometimes you have to walk a distance and that's not always clear. There's also the people and getting around them.
N5	4	It depends on the airport. Foreign countries and their language make travelling Independently more difficult.

Table 9.12: Participants' ratings and comments for airports.

Airports present similar behaviours and challenges to bus terminals for VIPs; this is particularly in orientation challenges (7 responses) from large boundaries and the increased number of tasks in an airport, including finding the entrance, check-in, the correct gate, or even sighted assistance (where 4 respondents expressed difficulty in obtaining this when needed). However, sighted assistance appears to be the primary coping mechanism for VIPs, as was positively referenced by all B and CVL participants. The PVL group predominantly referenced using visual function and identifying signage, with no mention of sighted assistance.

Compounding the orientation challenges faced by VIPs is that familiarity was not felt to improve performance in these settings, only appearing in 2 NSP responses. Consequently, references to difficulty or fear in certain scenarios appeared in 5 VIP responses, although negative perceptions of independence and safety only appeared in 2 responses. This reflects 4 fewer appearances than in bus terminals. An explanation for this is that all VIPs referencing orientation challenges and the impact of human assistance also described a degree of certainty in being able to find this assistance, and that most airports include a support service or other pedestrians that could facilitate this (with the exception of foreign airports mentioned by 2 VIPs where assistance may not be readily available).

Moreover, as was referenced by V3, V8, V10, and N2, airports appear to present the initial challenge of finding the check-in desk or sighted assistance, but then becomes more chronological and controlled upon doing so. Arriving early and planning ahead were referenced by 2 VIPs to further lessen orientation challenges. When paired with V2's comment in that airports present less hazardous obstacles than train stations (platform edges), this may explain why airports ranked 4 and 7 places higher than through stations and bus terminals, respectively, according to mean VIP ratings. This was not the case for NSPs where airports were rated lower than through stations, although similar factors including congestion and orientation issues were referenced by this group.

9.2.13. Shopping centre

Table 9.13 includes participants' ratings and comments for shopping centres.

ID	C	Comments
V1	1	Same as airport. I need boundaries to understand my space. I need to know where everything roughly is.
V2	4	Don't often shop alone, but when I do it is not usually in a mall, and I often call out for help when I get to the shop. In shopping centres, I've got to find an individual shop, and this is what I need help with, although generally not a big problem.
V3	4	Standard walking area is like a street, so the main issue is tripping on obstacles like wet floor signs. Obstacles are bigger issues than wayfinding.
V4	3	Don't like them, and I don't like shopping and the crowds that are coming from all angles. It's disorientating, very chaotic, and has many draws on your attention. I have gotten lost in Westfield Shepherd's Bush.
V5	2	No point in navigating if you can't buy the item. I always want to buy things when I go shopping and don't like navigating for no reason. It's alright if I go for a one-off item because I can ask the seller for assistance, but I cannot ask for too many items. Amazon is more useful for this although I still don't find shopping very accessible.
V6	3	Quite spacious but depends on what day you go as it's difficult when it's more congested. People on their phones and popups are problematic. I can get to the shops I know, but struggle with unknown shops. Finding places online in a shopping centre is hard because directions are usually unclear.
V7	4	The chances of finding a deserted shopping centre are minimal. Either I've planned it or ask for help. I rarely go on my own as I don't like shopping.
V8	1	I would definitely ask people to guide me to the shop, especially if there are many obstacles in the pathway like stalls. Escalators can be issues as I might not find the right one, or if it's going up or down.
V9	2	Don't like them. The lighting is too bright and there's usually too much glass. I generally can't see the name of shops due to reflections and this lighting, and the glass roof reflecting on floors causes glare. It's very difficult to get around.
V10	4	All the shop signs are too high in places like Westfield, it's a design style. I recognise shops by colour and brand, instead of just text. I can't do this if there is a long glass panel between shops, I wouldn't see them or recognise them. I sometimes have to go into shops to ask them which one they are, but I do like to browse around.
N1	4	Tend to have low mobile signal so it's difficult to contact people. Many are disorganised, such as having clusters of shops in halls.
N2	4	I hate Westfield because you don't know where to find a store and can't use tools like Google Maps. I find it much easier in places like Oxford Street where you can use Google Maps. It's still better than an airport as, In a shopping centre, you can walk around without having to be somewhere or under a time limit.
N3	4	Walking around is ok, but getting to a specific shop or place takes longer. It's not so straightforward sometimes.
N4	3	I tend to avoid these places as I want to go to see one specific thing or shop, I'm not someone that wonders around and shops. If I need something specific, I need to know where I am going.

N5	3	I don't get on well in those places. I've been to Westfield many times but still can't find my way around it, particularly identifying the right entrance and exit. The signs everywhere look the same.

Table 9.13: Participants' ratings and comments for shopping centres.

Shopping centres showed a mixed range of challenge areas for VIPs, primarily in orientation (negatively referenced in 5 VIP responses), but also in obstacles, signage, congestion, boundaries, lighting, and wayfinding technology, appearing in 3, 2, 2, 1, 1, and 1 negative response, respectively. Sighted assistance remained the primary coping mechanism, particularly the majority of the B group (3 responses), and 2 from the CVL group. The PVL group, similarly to other responses, continued to rely on visual function and identification to orientate in these spaces, finding obstacles and congestion to be primary challenge areas. It is notable that shopping centres scored slightly lower than airports even though these spaces can be hypothesised to be similar, including VIPs' rating of difficultly or fear in certain scenarios (appearing in 5 responses). However, on further inspection of feelings towards independence in shopping centres, positive responses were low (2) compared to airports (4). This could be attributed to the task of findings stores for shopping, to which 3 VIPs reacted negatively.

The inherent complex designs and layouts of shopping centres further exacerbates these challenges; a PVL, CVL, and B member each mentioned obstacles and pop-ups, which are typically dynamic, to be issues, and this is reflected in that only 1 VIP's response referenced the benefits of familiarity in these spaces. This suggests high or difficult cognitive demands in these spaces, exacerbated by their congested and visually demanding nature (expressed in 4 VIP responses). For instance, V9 described that they simply 'do not like them', citing excessive brightness, glass, and reflections as pain points.

It is notable that shopping centres were poorly rated by NSPs, with all 5 NSPs describing orientation issues. Insufficient indoor communication and navigation technology performance contributed to this in 1 VIP and 2 NSP responses, although the remainder attributed this to inherent difficulties in finding the right stores given the layout and size of these spaces, including congestion. Similarly to VIPs, 3 NSPs described negative sentiment to the task of finding stores for shopping.

9.2.14. Commercial unit

Table 9.14 includes participants' ratings and comments for commercial units.

ID	C	Comments
V1	3	3 in unfamiliar and 4 in familiar. If I knew the shop, like my bank, I would bravely go in towards where I can get help and would be quite confident. I have no idea of the layout of an unfamiliar shop, and smaller spaces are better as I might want to experiment and help myself a bit more.
V2	4	They know me at my local supermarket. I enter and step to the side, and they come to me, bring items, and take money. In other shops, I have to speak up and be polite, and so shopping is therefore not a problem, even at jewellers.
V3	4	The issue is reading tiny tags and identifying products, like using the Sainsbury's bakery section.
V4	4	Easier as it's more uniform. Still a bit chaotic and I don't know which aisle is which.
V5	3	You have so much to remember in big supermarkets, but I can remember where I need to go better in small shops and can also ask them for help.
V6	2	When I'm in a unit it's hard to pick out a specific item, certainly harder than finding a whole store in a shopping centre. For instance, if I want something from a fridge which I cannot see, I have to go to customer service.
V7	4	I'm always going to find help. It was my partner's birthday and I had to choose a store, so I went in and waited. I wanted to see if someone would come and help. In stores that don't help me, they lose my business. I am going to these stores for a particular purpose because I can't browse, so I need their help and go with a good attitude that is not demanding.
V8	1	I'll find a member of staff and they'll take me around. I go to a couple of supermarkets regularly and they know me, so they take me around the shop. I could not do it on my own.
V9	3	Not too bad with this. Once you find one thing you know which section you are in, I then use my magnifier for dates on food and so on. I don't like the big stores, and prefer the express and smaller stores.
V10	5	I go to my local shop every week. I choose to go there because I know it will be easy to navigate. If I think a place will be hard to navigate and I have a choice, then I'd avoid it. For instance, I find Tesco packaging harder to read than Sainsbury's, and Morrisons is really difficult, so I'd avoid them.
N1	5	There's enough space to walk around and get what I need. Some spaces can be tight and crowded but this doesn't affect my ability to navigate.
N2	5	If aisles are labelled correctly then it is easy to find what I want, but it can be tricky if aisles are not labelled. After going to multiple supermarkets, you get an idea of where things are positioned, like sandwich sections and checkout.
N3	2	I lose myself in them. I sometimes go in and go around and never find the stuff I'm looking for. I lose more time than I have to.
N4	4	I like wondering around a supermarket and am usually familiar with them. It takes me longer to find what I am looking for when they change aisle or item arrangements.
N5	4	I would feel safe here, it's only the smaller issues of finding where items are.

Table 9.14: Participants' ratings and comments for commercial units.

Retail units performed significantly more positively for VIPs, and marginally more positively for NSPs, than shopping centres. This improvement can be attributed to the ability of VIPs and

NSPs to familiarise themselves within shops, appearing in 4 VIP and 2 NSP responses. This correlates with the smaller boundaries of shops, to which 4 VIPs responded positively. Additionally, the ability to find sighted assistance was positively referenced 6 times by VIPs, including all 4 B participants. Consequently, general negative perceptions of independence or safety only appeared in 2 VIP responses. However, almost all VIPs (8 responses) and 2 NSPs discussed difficulty in certain scenarios, particularly in large or unfamiliar shops with unclear boundaries. Therefore, while the variability of performance in different retail unit types can vary, VIPs appear to favour and frequent local and smaller shops where staff assistance and familiarity allow for effective use of the space.

Both PVL participants were unique in referencing visual function with one discussing challenges in reading labels and the other describing improved uniformity within these spaces. Unlike spaces with larger boundaries, it also appears that obstacles in smaller spaces are less of a concern for participants as these were not mentioned by any participant here. Such is also true for the complex visual environments and layouts presented by retail units, through stations, and bus terminals in that orientation challenges were not referenced within retail units by all but 1 VIP, a significant decline relative to these other environments.

9.2.15. Restaurant/Eatery

Table 9.15 includes participants' ratings and comments for restaurants/eateries.

ID	C	Comments
V1	1	1 in unfamiliar and 2 in familiar. Less confident than when I am in a shop because I worry about the layout and bumping into people and spilling their food.
V2	4	I have to speak up to get help when going in alone, finding a table, and finding a seat, but I don't like eating alone. Some restaurants are reluctant to take a dog.
V3	4	Don't know where the tables or chairs are sometimes, like their edges or angles. People usually aren't an issue, it's the placement and angle of chairs and furniture.
V4	3	Usually not a problem as someone takes you in to the sitting area, but if it's ordering from a counter then I do not like them. The clearly displayed price list and menu are out of my sight range and so I have to walk to the front to see it.
V5	3	I have to do my research online before going, especially for the menu, although this is not always helpful as it's not always available.
V6	3	Some are harder than others, but staff generally help me to my table. Some smaller ones like Greggs or Subway where things are self-service are complicated and staff don't understand that I need help. They can't come round to help or are too busy.
V7	4	Finding a restaurant and asking for help is no problem. Some visually impaired people want to be independent and want to be able to read the menu alone, but actually it should be a social experience and I prefer to chat and learn more about it. I never say no to help, it can deflate people if I do. It makes a big difference.
V8	2	If on my own, I'd stand by the door and find a member of staff to take me to a table. They would usually read the menu to me. I find them easier than other places because of the staff member on hand, and they are good if they know you have a visual problem.
V9	3	When going with friends, I will follow them in. I generally walk quite slowly to avoid steps, and use the magnifier or take photos of the menu to see it. Lots of them have downstairs toilets and so I have to go with someone else. Cafes have menus on walls, and I can't read these, and the staff may not have time to help.
V10	5	I would ask for help with the menu, reserving a chair, and everything else. I wouldn't ask someone to read the whole menu, so I curtail my choices. I would ask to be shown the toilets. I'm open to saying I'm visually impaired and being thankful for help. I'm fairly comfortable because I'm happy to be there on my own, but it's challenging when there's lots of people and I have to find a free space when it's dark.
N1	5	Similar to a shop in that space issues with pulled-out chairs and tables can be restricting.
N2	5	Mostly greeted by the waiter who takes me to my seat.
N3	5	I'm fine with them and have no trouble finding the table or toilets.
N4	4	I don't go out to eat very often and, if I do, I want to find a quiet spot next to a wall. I like more private spaces.
N5	5	You're usually moving around less, and only have to move if going to the toilet. I tend to ask the waiter or waitress if I need help.

Table 9.15: Participants' ratings and comments for restaurants/eateries.

Restaurants and eateries scored very similarly, in considering average ratings, to retail units for VIPs, and significantly better for NSPs. However, differences can be seen in how the different visual functions scored in that, while the B and PVL group scored restaurants lower, on

average, than retail units, the CVL group scored them higher. The characteristics raised by each group were varied, however, sighted assistance and interaction with waiting staff were by the far the most prevalent, being referenced by 9 VIPs and 2 NSPs. This is perhaps given the inherent mechanisms of visiting a restaurant where interaction with waiting staff is expected. These interactions were not always positive, with VIPs voicing positive and negative sentiment 9 and 3 times, respectively. V2 related this to some restaurants' reluctance to accept a guide dog, while V6 explains how smaller spaces restrict staff from being able to physically assist them. Interestingly, V10 describes curtailing their choices given that they would not want to ask someone to read an entire menu.

Other prevalent issues were finding a seat, and this was referenced by each VIP groups across 4 responses. However, it appears that sighted assistance addresses this issue in that 6 VIPs expressed difficulty in certain scenarios in restaurants, 2 less than retail units, pertaining to avoiding steps (1 response), an inability to read menus (3 responses), and avoiding obstacles (2 responses). NSPs scored restaurants near perfectly, with only N4 scoring a 4 from infrequent use and a desire to find a quiet and private setting.

9.2.16. Hospital

Table 9.16 includes participants' ratings and comments for hospitals.

ID	C	Comments
V1	1	I feel slightly better in familiar hospitals and might give reception a go, but hospitals are usually unfamiliar places.
V2	4	Usually ask for a hospital porter which are very useful. I therefore don't find hospitals daunting, I find them quite relaxed.
V3	4	Same as in a restaurant regarding the waiting area chairs, but hospitals are usually well lit, so this is less of a concern.
V4	4	Somewhat like stations but a little bit easier. I have no particular issue with the seating area, but have more of an issue of tuning into the signage and how it runs, such as finding the right department. It's usually ok, but temps (temporary employees) can be a bit more chaotic than typical reception staff.
V5	4	I often go there and therefore often know the routine and places I need to be. Sudden visits are the problem, then I don't know where to go and signage does not help.
V6	2	No two hospitals are the same. I've missed appointment not because of arrival time, but because of misguided information on how to get to the specific clinic which takes up to 30 minutes to find. Getting help is also difficult due to different wards, so it's generally hard to get around. It can take me up to 40 minutes to find my wife in a hospital.
V7	4	Getting to the hospital is not an issue with tech, either walking or in a vehicle. Hospitals are never empty of people, there's always someone at the door or on a desk, and they are all easy to find and helpful.
V8	2	Transport to hospital entrances can be hard to navigate such as the bus stop in front of Moorfields Eye Centre at Ealing Hospital. Trying to find the entrance is the biggest challenge but, when I do, I get to the front desk, they find me a porter, and it is easier from there. So, I always try to find a passenger to help me find the entrance and desk.
V9	2	They're terrible. Long corridors and hard to find signage placed up high near the doors. 'Are there any staff around to ask for help?'. I often get sent around in circles.
V10	3	They're somehow harder to navigate because the receptionist cannot move from reception, so getting someone to help is not always possible. People are not always good at giving instructions (like right or left), or are not used to guiding blind people. This applies everywhere, actually. Hospitals are complicated, but signs are often too high. Their corridors and facilities are usually the same colour all over, and this makes it more challenging. Something is usually wrong for me to be in hospital, and this anxiety transfers to my sight.
N1	4	Decent signage usually, but I can still get lost. There are enough facilities and seating areas for me but there may be a wait on occasion.
N2	3	If there's a front desk that is easy to find and at the entrance, then you can ask someone where to find things. I definitely need help to walk around.
N3	4	Not used to them but I once attended one and it went well.
N4	3	It is a bit difficult to find my way around, generally because they are vast places. Even when you find a ward, there might be no one there to ask where you need to go. It's generally much easier to have someone explain than to follow a set of signs.

N5	4	It can get slightly confusing as to where you are going, they're not well-signed for visitors.

Table 9.16: Participants' ratings and comments for hospitals.

The response to hospitals was mixed for the VIPs, but quite negative for the NSPs where hospitals and shared spaces were ranked equally, and penultimately from the worst-rated environment (stadiums), on average. Poor or unavailable sighted assistance was a prevalent complaint by VIPs, appearing in 4 responses, although it is surprising to note that none of these were from the B group who presented 2 positive responses to the usefulness of sighted assistance. Signage was another particularly challenging aspect of hospitals, with negative sentiment appearing in 4 VIP and 2 NSP responses.

Surprisingly, one of these respondents was from the B group. Indeed, VIPs from all 3 groups responded negatively to signage, with V10 also identifying poor contrast in hospitals from uniform colours. V3 suggests that hospitals are well-lit, although seating issues similar to restaurants prevail. This may suggest elevated effects of different visual function in hospital environments, hence such a mixed response across groups. Familiarity in hospitals does play a role in the ability to navigate them, as referenced by 3 VIPs (2 of which being B). Ultimately, however, in considering signage and sighted assistance issues, 6 VIPs and 4 NSPs cited orientation problems in hospitals, particularly in finding someone to help across entrances and different wards, and accessing signage that is poorly positioned. This ultimately led to a relatively high proportion of VIPs and NSPs to report difficulties in certain hospital scenarios (6 VIPs and 2 NSPs).

9.2.17. Local clinic

Table 9.17 includes participants' ratings and comments for local clinics.

ID	C	Comments
V1	2	Better than hospitals because the area is much smaller, and reception is easier to find. There are only certain places where things can be.
V2	3	Can sometimes be a bit chaotic, especially some receptions, although my local clinic is ok. I am sometimes asked to a take seat but have no idea where to sit as there is an open space of seats and I am not sure where people are sitting, yet they may not help as patients usually sit quietly and don't say anything. Some blind patients may not be as competent as I am, and this doesn't help them.
V3	4	Same as a hospital, including the waiting area. Reception is usually helpful.
V4	5	Usually less options and choice, so you land where you need to be as there is less room for error. A minimal need to worry about where to go, it's a reception desk and a row of chairs.
V5	4	You're the client and you pay for it, so I do not hesitate to ask them for help.
V6	3	Been to a few and they're smaller, so this helps. They tend to help and direct you easier. Most places direct you to seating but it was harder in the pandemic due to blocked seats and sitting on hazard tape.
V7	4	Same as a hospital, they're never going to be empty.
V8	3	I typically go to the same place and have been doing so for around 40 years, so I know the layout and where to go. Occasionally, I might need help from the receptionist given a new upstairs section (and I might need help going upstairs) but most of it is ok because the more I do something, the better I get at it.
V9	3	They're ok as I tend to know them, like my local GP. I've found that, when taking a friend to their one, it can be slow because it's unfamiliar. Going to a new clinic and finding my way around it is the issue.
V10	3	I don't go too often so they're likely to be new places and my anxiety will be higher. It's the unknowns, made worse by COVID where you can no longer be early and have to be there at the right time.
N1	5	I tend to navigate small spaces easily.
N2	4	Same as a hospital in that you need a front desk at the entrance and will need to ask people where to go and what to do. I've rated them higher than a hospital as they are usually smaller.
N3	4	They tend to have less information to navigate around, but I really like to have information and to immediately get to where I need to go.
N4	5	Usually much smaller than hospitals. You're told to take a seat and someone calls your name.
N5	5	They're very small so I don't usually have to move around too much.

Table 9.17: Participants' ratings and comments for local clinics.

The parallels between a hospital and a local clinic are very similar to those between a shopping centre and a retail unit; local clinics were rated substantially more highly than hospitals by both VIPs and NSPs. A reoccurring theme and causal factor are the smaller spaces typically presented by local clinics versus hospitals where 4 VIPs and 4 NSPs reacted positively to this in their responses. This therefore leads to a better ability to attain assistance, referenced positively by 5 VIPs and 2 NSPs. To this effect, orientation was therefore improved, referenced positively by 4 VIPs and negatively by only 1 VIP. Subsequently, positive perceptions to these spaces appeared in 5 VIP responses and 2 NSP responses, a notable improvement from

hospitals where orientation was referenced negatively in 10 responses across all participants with no positive references.

While local clinics scored highly, it is important to note the effect of familiarity in these spaces in that participants mentioned high familiarity with their local clinic, and new clinics may therefore pose significant effects on confidence. This was referenced by 4 VIPs, such as V9 discussing how finding their way around a new clinic to be an issue. V10, who does not often visit clinics and is therefore not familiar with them, emphasises this finding. V2 made the interesting observation that detecting empty seats can be a problem as patients typically sit quietly, especially for other visually impaired individuals who may not have the confidence to seek help. Similar observations were made in hospitals and restaurants, and seat detection in these spaces should be considered as an important requirement when sighted assistance fails to be effective.

Finally, it is noted that these issues did not disproportionately affect a certain group of visually impaired people as no detectable trend between sentiment and visual function was found. This was not the case for lower-rated spaces with more demanding multisensory interactions. Bus terminals are an example of such given their higher dependence on visual reference points, and CVL and PVL groups were therefore disproportionately affected by signage and contrast within their responses.

9.2.18. Public house

Table 9.18 includes participants' ratings and comments for public houses.

ID	C	Comments
V1	1	Would be similar to a restaurant. If known people were going, then I would experiment. I am less scared if someone sees me coming in.
V2	4	I am quite happy and feel safe as I very rarely go in on my own.
V3	3	On first entrance, I am usually concerned that it might be dim with obstacles in places. After I walk around, I get more comfortable.
V4	4	Will have trouble finding the loo, especially in big and dark clubs that make it hard to work out. At a bar, I may struggle more to choose my table by working out which table is accessible and free.
V5	4	I can navigate myself around in a pub, and contactless payments have made paying much easier.
V6	2	Even in the ones I know, it is difficult to find a table, 'is someone sitting at that table?'. You also have to go to the counter to order, and this makes it harder. It's also quite dark, the lighting is not good enough to get around.
V7	4	If it's my round and people are at the table, I will order it and can do it. The barman sees my cane and brings the drinks over, or I hand over my card to a friend. We have to teach the world rather than expect the world.
V8	2	Similar to a restaurant. Finding the entrance to the pub and any stairs might be a challenge. Sometimes you have to go to bar to order food and this is another challenge. I almost always find help as people see that I'm struggling a bit and they come over. I am usually with friends, and they might also be visually impaired, but if I go with sighted person there are no issues. I always think of the worst-case scenario and try to do it myself.
V9	2	Generally carpeted and dark, so more difficult. They usually have steps that you don't know are there, but their menus are not too bad, and you tend to be sitting at a table so less walking around. In a new pub, I wouldn't explore or know if my friends were already in.
V10	4	Noisy and dark so, if you are meeting someone, you have to plan to phone each other and meet. Because people are drinking and excited, I don't know how they might react if I bump into them. Going in a group makes me feel better.
N1	5	Similar to restaurants in that I can navigate the space easily, it can just get crowded sometimes.
N2	5	Same as a restaurant in that I would go to the waiter and ask where to sit. Finding my way to the bathroom can be a bit tricky though.
N3	4	I'm usually dizzy and in a different headspace, so am more distracted.
N4	4	Can be busy and, if you're looking to meet someone, it can be difficult in a busy pub.
N5	5	They're often very similar to each other, and it's usually a small area.

Table 9.18: Participants' ratings and comments for public houses.

Public houses were rated, on average significantly worse than restaurants by VIPs, and only marginally worse by NSPs. This is notable as 4 responses (2 VIPs and 2 NSPs) explicitly noted that their experiences in public houses were similar to that of restaurants. However, on further investigation, while dependence on sighted assistance at public houses was similar to that in restaurants (referenced positively by 5 VIPs and 1 NSP), negative sentiment to the poor lighting in public houses prevailed and appeared in the responses of 5 VIPs. Particularly, only the PVL and CVL groups mentioned this aspect within their responses. Additionally, these groups also

referenced issues with obstacles (4 responses) and navigating around people and seats (3 responses), suggesting that reduced visual function can be problematic in certain dimly lit public houses (4 CVL and PVL responses).

Negative sentiment from the B group primarily considered orientation and finding entrances, tables, and the bar (2 responses). However, on collating responses from all VIPs, 5 responded positively to independence within these spaces, with only 1 B VIP expressing an unwillingness to independently explore public houses without assistance. These figures are similar to those obtained for restaurants even given public houses' lower overall rating. Negative sentiment to lighting was not mentioned to such an extent for other environments as it was for public houses (being not referenced at all in restaurants), and could therefore be argued to be a major contributing factor in public houses' reduced rating by VIPs (particularly by the CVL group).

9.2.19. Museum

Table 9.19 includes participants' ratings and comments for museums.

ID	C	Comments
V1	1	Difficult to navigate and not much chance of going around by myself. Always scared of knocking something over. No structure to the walking path or building, and no sense of shape or size. If I knew where things where I would have a go. Open and tall room sizes make acoustics hard to determine.
V2	3	Hard to navigate on my own as they are big and spacious, and I have to know what's where. I am confident being in one, but getting around one is problematic.
V3	3	Same reason as a pub in that I need to familiarise myself with the area to be confident.
V4	3	Struggle to access them. Even at the exhibit I'm not sure if I've gone the right way. It draws attention to me and there is an effort of access in that accessing an exhibit is hard work, and It is usually just a sign with a little write up, so it feels dry. More modern setups are getting a little better and more interactive, and sound systems help.
V5	2	Very visual. I would love for each display to have a sensor and audio so, if you can't see, at least you can listen. I go with people and, before COVID, museums hosted special audio described and accessible tours. They select a painting, magnify and 3D it to make it accessible. This was very useful but has now stopped.
V6	1	There are few exceptions such as open-air museums, but in most museums, like the science museum, there is stuff everywhere, like so many boards that need magnifiers, and so many arrows and walkways to follow. We much prefer guided tours and don't like using the magnifier because there is so much to read, and it's not that interesting.
V7	4	As a trustee of VocalEyes, I like the arts. The chances of going to a museum on my own are fairly low. I like making it a social experience and, if I go with a friend, they will meet me somewhere convenient. I will only go to a place that I would enjoy. No way would I walk around on my own as I don't see the point. A curator saw me with the white cane and let me touch exhibits that no one else would be allowed to touch.
V8	1	I've done research for them in the past to help them develop apps for visually impaired visitors. A museum is a big place, and I would need a sighted guide to get around. I am not there to navigate; I want to see what is there.
V9	2	Dark and hard to find my way around as you're not always having to follow signage and may be going with the flow. The good thing is that there might be steps but they're not always in your path, so I'm not expecting a trip hazard.
V10	4	They have people at every room, and this is helpful because I can't always see the exhibit number. They help me enter this into the audio-description device. There are specific guided tours that I attend, and these are brilliant because I don't like having to stand back, and like being close to the exhibit. Some people take photos and enlarge them, but I want to be able to enjoy art and culture up close.
N1	5	They're large open spaces so less tight when congested and easy to navigate because of good signage.
N2	5	It's easy. They ask you to walk in a specific direction In most museums and, If you get lost, you can always find your way out as there is no rush and you don't need to be in a specific place at a specific time.
N3	3	I like to wander, but some are not well-organised. They're meant to make you get lost in them on purpose, they planned this layout.

N4	4	Very comfortable but, if I look for a particular section, it can take a bit longer, especially with lots of people around.
N5	4	I suppose people are not so familiar with them because you don't go that often. They're designed to take you around a certain route which is a good thing.

Table 9.19: Participants' ratings and comments for museums.

Museums were the worst-rated environment on average by the VIPs, tied with bus terminals, but received mixed ratings from the NSPs. Quantifying the themes within responses evidence that museums pose a range of challenges for all VIP groups. Boundaries were problematic for 3 B and 1 CVL participants, particularly in that museums are larger and more complex spaces requiring increased orientation effort. Avoiding bumping into obstacles and exhibits was referenced by a CVL and B participant, and poor signage was referenced by 2 CVL and 1 PVL participant. Lighting was also negatively referenced by a CVL participant.

As a result, orientation was negatively referenced by 5 VIPs across all groups, without any positive reference. Contrarily, orientation by NSPs was positively referenced in 3 responses, with causal factors including a lack of time pressure, open boundaries, and their purposeful route design. Further observation of answers reveals that the strongly visual nature of museums increases the disparity between the VIP and NSP responses as vision is often a requirement of enjoying the use of these spaces (as referenced by 2 VIPs). The mechanisms to cope with this appear to be available or in development, but not consistently implemented. For instance, V5 wishes for exhibits to include automatic auditory feedback, while V4 explains the difficulty in access that this creates, although stating that modern systems are improving in this regard. V6 does not prefer the use of magnifiers to visually detect their surroundings, instead valuing guided tours over the use of technology.

Furthermore, the need to attend a museum with someone else was referenced in 5 VIP responses, with 2 B VIPs stating that they would not be able to attend these spaces on their own. Negative references to independence similarly appeared in 5 VIP responses, counteracted by only 2 positive responses in this context. This suggests that museums, while less critically rated in navigability than other expansive spaces such as bus terminals (5 versus 7 negative responses), present inconsistent availability of sighted assistance and technology to overcome the visual nature of the task at hand, thus reducing VIPs' ability to enjoy their use of the space.

9.2.20. Theatre/Cinema

Table 9.20 includes participants' ratings and comments for theatres/cinemas.

ID	C	Comments
V1	1	Acoustics in cinemas don't help with orientation because of room size, like in museums. There is no echo in the room, only a dull sound, and I can't tell where I am in the vast space.
V2	4	There is plenty of help at theatres, and they are compact and easy to get around.
V3	2	Usually very dark on entrance and so I use my phone torch. Seeing the seat number is a challenge.
V4	2	Terrible at finding a seat. Adaptation time is part of the trouble and that slows me down. Where is the seat number?
V5	2	I would rather watch on TV because I have audio description. Not all cinemas and movies have audio description, so I do my research and phone them in advance to ensure accessibility.
V6	3	In the most part, once you get to the entrance, people help you. Getting around alone is difficult and we would never find our seat, but they know that you are visually impaired and come to help you, and take you at the end of the show to the shop and exit. The box office, bar, and shop are shockingly bad though because they have limited time for you.
V7	4	It's a social experience. Audio described performances give you a touch tour on stage and you get to see minute details that no one sitting would ever see.
V8	3	Usually good at the desk. They help with tickets and arrange everything, especially if I call up before. When I find a member of staff it is plain sailing, once they upgraded us and put me and a friend in the front seats.
V9	3	I go to the cinema a lot and generally know my way around them, though entering and getting to the right screen can be difficult because it's dark and carpeted. Cineworld at Leicester Square is a particularly bad example as it has a lit up staircase with screens. In cinemas, even if early, I still can't see the seat number on seats. In theatres, I'm more likely to get help to my seat, but they still have the same overall issue of being dark and carpeted.
V10	4	I go to the third row from the front. it's a social experience and I don't go on my own. This is why I feel comfortable, otherwise I'd have to ask where everything is and I'll have a slight anxiety, 'am I going to the right place, loo, show?'. The white cane helps and gives you a reason for asking.
N1	4	Theatres can get very tight on space so getting to my seat can be difficult, it's a congestion issue.
N2	4	They're usually dark and it's hard to find the row number. I need to use my flashlight and step over people, so it's not a great experience.
N3	5	I'm very confident because I'm used to them.
N4	4	I usually have a ticket with a seat number, and I just have to make sure I get to the right seat. I want to get in there for good time, I don't want to inconvenience others by making them stand for me to pass.
N5	4	I don't go that often but, when I do, I usually go to different ones.

Table 9.20: Participants' ratings and comments for theatres/cinemas.

Cinemas performed poorly for VIPs particularly in identifying and navigating to their seats. Both PVL participants and a CVL participant expressed that dim light (and poor visual function) affected their ability to find their seat, and this was reiterated by another participant with CVL for similar reason, adding that the carpeted nature of theatres and cinemas further

reduced their accessibility. Orientation challenges persevered for another CVL and B participant, with the B participant citing that the acoustics in these spaces are similar to museums in that they are not useful for orientation given the vast nature of the space. This was contracted by another B participant that found them to be compact and easy to navigate, suggesting that VIPs can present very different experiences regardless of similarity in visual function.

Sighted assistance and the presence of others was a prevalent positive factor referenced by 6 VIPs, particularly in finding seats and navigating the space. However, V6 did identify problems in seeking assistance within the box office, bar, and shop resulting from time constraints on staff. V5 included the issue of not all cinemas being accessible and providing audio description cinemas. As a result, 6 VIPs expressed difficulty in navigating these spaces, and only 3 VIPs expressed general independence and comfort when operating within these spaces.

Interestingly, N2 described a similar experience to the PVL group in that they needed to use their flashlight to identify the seat number, and that this task was generally problematic. Dim light vision is therefore an important determinant of the ability to identify the correct seat within this context. Responses from other NSPs, however, did not correlate with VIP responses in that other NSP responses referenced congestion, arriving on time, or familiarity as detractors within theatres and cinemas.

9.2.21. Stadium

Table 9.21 includes participants' ratings and comments for stadiums.

ID	C	Comments
V1	1	Don't really go. Been when younger but not for a long time. Have to go with someone. Crowds are problematic with everyone being in a hurry.
V2	4	Would never go alone and sighted assistance is needed, although it is a nice experience.
V3	3	I don't usually go to stadiums, but finding the seat might be a challenge.
V4	3	Finding my seat is still difficult, and knowing where the numbers are, but I get directed to the right aisle eventually.
V5	4	Too many people, and it's not comfortable since I've lost my sight. I would go with someone.
V6	3	Very little experience as I don't go watch football matches. I imagine people would help me, and I would never go on my own as I would need this help. There's going to be people around and stewards, and this makes things better.
V7	4	The chances of going alone are so slim and, even if I did, I can get help.
V8	1	Lots of people and crowds make it difficult. Finding the right place, like a specific gate, in these vast areas is not possible on my own and I would therefore not go on my own. I would need a sighted guide.
V9	2	So many steps, there's not always a rail to hold on to, and not much colour contrast on steps. It's difficult, and I wouldn't go on my own, I'd always be with someone else.
V10	4	Don't usually go, but I'd need my binoculars. It was amazing to be amongst a crowd in a live event. The drinks were also lovely. It's fairly chaotic but usually organised well enough. Visible staff makes a huge difference, like those wearing special clothing, because knowing who to ask for information takes the stress away.
N1	4	It's a large space but also a large volume of people, so there are congestion issues.
N2	4	I can't find my seat without asking for directions and I don't like crowds here as each person has to go to a different space. I like crowds like when exiting a station where everyone is going in the same direction.
N3	3	I don't go to them frequently, and ticketing and seating is hard to find.
N4	2	I don't go often. I can navigate around, but this is an environment I don't like because of crowds and mob behaviour. Trying to get around is sometimes like swimming against the current, especially getting out or getting in, it makes it difficult to move.
N5	3	There's often a large amount of people at stadiums, so I feel anxious and corralled in.

Table 9.21: Participants' ratings and comments for stadiums.

Stadiums were the worst rated environment by NSPs and received mixed feedback from the VIP group. As a result, stadiums showed the smallest disparity between average VIP (2.9) and NSP (3.2) ratings of 0.3. The most prevalent theme in VIP responses was that they would not go to stadiums independently (7 responses) and that sighted assistance would be helpful (9 responses). Stadiums therefore required sighted assistance regardless of the VIP's visual function. Including orientation issues in identifying the right seat (3 responses), other issues preventing VIPs from accessing these spaces were congestion (3 responses), obstacles (1 response), steps (1 response), and poor colour contrast (1 response).

Congestion was the primary pain point for NSPs, referenced negatively in 4 responses. This elicited feelings of anxiety and 'swimming against the current', as described by N5 and N4, respectively. A concurrence between the VIP and NSP group was that this was the least frequented space, with 4 VIPs and 2 NSPs stating that they do not often go to stadiums. This may affect the depth of responses provided by users, and it is unclear whether or not this is a result of visual impairment. Ensuring the provision of sighted assistance, clearly visible staff (as described by V10), and congestion management may therefore be the optimal solutions for addressing challenges within stadiums regardless of visual impairment.

9.2.22. Office/University building

Table 9.22 includes participants' ratings and comments for offices/university buildings.

ID	C	Comments
V1	1	Like a hospital. Would need assistance from the beginning.
V2	3	No particular reason.
V3	5	Never struggled in these places as they are usually well-lit with no random objects in random places. They are very 'uniform'.
V4	4	Visually, I do not feel less able than someone without an impairment. The same signage problem persists but it's not a big problem usually, just in an unfamiliar new layout.
V5	4	Got people around that I can ask, but even coming to the experiment was a hurdle because of coming down the steps and small obstacles. Carpets and edges are the same colour, so they need more contrast and colour.
V6	2	If coming on my own, I would not be aware of the obstacles and there is less likely to be a dedicated reception area. There are fewer reception areas in universities and loads of corridors to get lost in, so a lower chance of getting help. Universitas are very spread out with different buildings and, if I come in the wrong entrance, it is easy to get lost. Someone watching in the CCTV room probably won't radio in for someone to help me.
V7	4	In the beginning, I would get someone to help. People leaving obstacles behind make it difficult, like open drawers, cupboards, and bags. I learn my routes quickly and always use my white cane.
V8	1	I didn't know where I was supposed to go for this experiment, I didn't know where the building was, so that's why I had to arrange someone to meet me. I would need assistance as I couldn't navigate these spaces on my own.
V9	2	Difficult to get around, but at least you know there won't be a random step to trip on. Bags, left items, cables, and chairs with wheels are the issue as they're trip hazards, especially loose cables that are not taped up. Lift buttons can also be very difficult to find.
V10	3	If it's my office, it would become like my house. I'd take my cane for the first two weeks but then I wouldn't need to anymore. The worst thing is recognising people. I worry about saying hello to the wrong person or not knowing who I am talking to. The social element is super important, and I do not want to do a social faux pas. To behave in a conventional way is important.
N1	5	Easy to navigate and usually have good signage.
N2	4	On the first day at my job, I had to go to reception to ask for the way around, especially when meeting rooms are not named or numbered chronologically.
N3	5	Usually well-informed and each room has its own location.
N4	4	It's one thing being in your own office but, if you're in another one, it can take some hunting around. I usually ask people and prefer it over signs. I have had trouble finding people for this, or they don't know the place you're looking for.
N5	5	I know where I'm going, I work in one. There are people around that can help, and they usually have their door open so it's easy to ask.

Table 9.22: Participants' ratings and comments for offices/university buildings.

Offices and university buildings were rated similarly to airports and stadiums by VIPs, on average. Contrarily, NSPs rated offices and university buildings more highly, reaching an average rating similar to hotels and local clinics. The PVL group produced the highest ratings relative to the other VIP groups, subsequently producing only 1 negative impression regarding

signage in their response. Otherwise, themes included positive perceptions to lighting, no randomly placed obstacles, uniform boundaries, and a good ability to orientate. Both PVL participants therefore produced a positive perception of independence within these spaces.

On investigating the B and CVL groups, however, issues across several themes arise, suggesting that poorer visual function has greater impact within these spaces. Randomly placed or small obstacles were problematic for 3 CVL and 1 B participant; V9 particularly identified bags, left items, cables, and chairs with wheels that cause a trip hazard. Other negative sentiment pertained to poor contrast between carpets and edges (1 response), loose boundaries (1 response), lift button visibility (1 response) and general comments regarding the ability to orientate within these spaces as a result (3 responses). The persistent thematic finding was that these were prevalent enough to cause difficulty for all 6 CVL and B participants in certain scenarios. Sighted assistance, while positively referenced by 3 B and 1 CVL participants, was not always readily available or easy to find, as negatively referenced by a CVL participant. Another CVL participant described the important of the social element in these spaces as they worried about saying hello to the wrong person or not knowing who they were talking to.

Familiarity within these spaces does alleviate some of these issues, as observed within 3 VIP responses. 3 NSPs also discussed a benefit of familiarity within their office space. 3 NSPs subsequently felt positive independence and an ability to navigate these spaces. Negative sentiment observed in 2 NSP responses pertained to issues or non-preferential use of signage (particularly rooms that are not chronologically ordered), as well as others not being able or available to provide wayfinding information, leading to orientation challenges. However, other responses were positive, particularly in orientation (3 responses), distinct boundaries and layouts (2 responses), and help from others (3 responses).

9.2.23. Private dwelling

Table 9.23 includes participants' ratings and comments for private dwellings.

ID	C	Comments
V1	5	Highly confident because its familiar. I noticed that I was scared when my sight was going, and I misjudged the position of things, but now I can almost 'see' the items. I have all the cues and boundaries, so distance measurement and judgement are better and quicker.
V2	4	Generally confident and should be a 5, but could be better as it needs tidying up and more space. I've tripped over in my own home.
V3	5	Home is well lit, and I know where everything is.
V4	5	I know where everything is. I can walk through blindfolded.
V5	5	I'm very familiar here. There are no steps or obstacles.
V6	4	Confident but my home can be quite cluttered. I'll put something down somewhere and finding it can be hard but getting around is easier and you know where obstacles are instinctively. The problem is when things fall over and you knock against things.
V7	5	Everything is set up the way I want it to be. My partner makes sure everything has a place and is easy to find. It's home.
V8	5	I've lived in my flat for 20 years so, when I navigate it, people might not tell that I am blind. I'm very confident here, but it helps when people don't move my items, and they are usually good with this.
V9	5	Know it like the back of my hand but the problem is that I am not always putting everything away, and may have problems finding things. I'm good with where I put things like keys and the remote control.
V10	5	Familiar, I know where everything is.
N1	5	Everything's organised and I can navigate through my stuff easily.
N2	5	I'm very familiar with my space.
N3	5	I'm used to my home.
N4	5	You know your home like the back of your hand. Kids' toys or the cat can take you by surprise.
N5	5	You're surrounded by your things, and it's set up to how you want it. Everything is as it works for you.

Table 9.23: Participants' ratings and comments for private dwellings.

Private dwellings were the best rated environments by both VIPs and NSPs, on average, and for very consistent reasons regardless of visual function. 14 responses referenced familiarity and how it is very high within these spaces. 1 B and 2 CVL participants mentioned that clutter and not putting things away made finding them harder or created a trip hazard. N4 similarly mentioned that kids' toys and their cat may take them by surprise. Overall, however, these were not sufficient to detract from the profound familiarity and comfort described within responses, translating into all 15 participants positively expressing independence and confidence within their homes. Indeed, V1, V4, and V8 (2 B and 1 PVL) referenced being able to 'see' items, walk through blindfolded, or have people not be able to tell that they were blind. Such a theme that directly decoupled visual impairment from being able to access an environment was not observed in other spaces.

9.2.24. Gym

Table 9.24 includes participants' ratings and comments for gyms.

ID	C	Comments
V1	1	Need assistance, but don't really frequent them. Afraid of getting in someone's way, and it's a dangerous area because of lots of activity.
V2	3	Haven't been recently but would be happy to go with assistance.
V3	5	Nothing is in a random place. Items are either in the centre or on the side, and the walking path is clear.
V4	4	Don't use them day to day but they can be hard work. Unfamiliar equipment and landmarks to navigate around.
V5	4	I have to go there because I have to exercise. No point in being negative about it. I go on my own but don't do anything difficult. There is trial and error, I feel around the weights or stick to what I know. I don't run, but I may do when I get more confident.
V6	3	A big part is familiarity, but I also have to be mindful of people and equipment. Most gyms that you use regularly will give you an induction so you will be comfortable. In a hotel with once-use gyms there are reception areas that will notice you are visually impaired. We don't use them that much but, when we do, there is usually help. I had to have inductions before using gyms.
V7	4	For all the same reasons as above. People who are visually impaired feel like they can't go to the gym, but they must realise that if they don't ask for help, then they won't get it. Why feel every dumbbell when you could just ask and have it given to you?
V8	1	I will need help, especially when finding certain machines. Health and safety are another issue, and some gyms tell me that I need to bring someone (sighted) with me.
V9	2	Don't go as I'm worried about walking into something or tripping over. Controlling a machine might be a problem, like finding the right button. Calling on the staff member every time would be inefficient and take longer.
V10	3	I can only turn the machine on or off, or go faster or slower, but not the other functions, so I feel left out. If people are exercising on the floor, then I wouldn't know if there is enough room. People expect you to be able to see. I have to ask how to use some machines.
N1	4	Quite confined spaces that can get easily crowded. Gym equipment has unknown etiquette, and uncertainty can cause traffic.
N2	5	Usually small to medium in size, and I feel more comfortable in smaller spaces indoors.
N3	3	Similar to a grocery store in that I sometimes feel like I lose more time than I need to when trying to find something, like a piece of equipment.
N4	3	I don't go, but I feel I'd be somewhere in the middle. I'm not sure what I would be looking for and don't know what half the machines do.
N5	3	I wouldn't say I feel particularly comfortable in a gym environment. It's quite intimidating because of the people there. You're using the equipment in a way that someone else might use better.

Table 9.24: Participants' ratings and comments for gyms.

Gyms received mixed feedback from VIPs, but were relatively poorly rated by NSPs, on average. Prominent issues were navigating gym equipment and other obstacles, including people and ground-level trip hazards, which were negatively referenced by 5 VIPs (3 CVL, 1

PVL, 1 B). Congestion therefore also saw negative sentiment from 3 VIPs, and was attributed to navigating obstacles and safety. For instance, V1 states they are 'afraid of getting in someone's way, and it's a dangerous area because of lots of activity', while V10 explains 'people expect you to be able to see'. NSPs provided a similar response where N1 describes that the confined nature of some gyms can cause crowding, while N5 feels intimidated because of the people there, and their use of equipment in a potentially superior manner.

While 3 B and 2 CVL participants referenced their critical need for sighted assistance within gyms, a CVL participant expressed negative sentiment regarding the time and efficiency required to obtain this. Use of gym equipment drew negative responses from 2 CVL and 3 NSP participants for similar reasons. Both CVL participants expressed that they could not use all the functions of gym equipment, with V10 stating that this made them feel left out. NSPs stated that they were unaware of equipment etiquette, would not know how certain machines function, or feel intimidated by others' use of them.

Unfamiliarity and infrequent use of gyms may have a causal role in reducing both VIP and NSP ratings in that 5 VIPs (2 CVL, 1 PVL, and 2 B) and 1 NSP do not frequent gyms, although 3 of these VIPs explained that familiarity would play a role in their use of these spaces. In concurrence with these findings, 4 VIPs and 1 NSP described negative sentiment to independence within gyms, while only 1 VIP and 1 NSP described positive sentiment. Finally, contradicting views between participants were noted; V5 stated that they would use trial and error, and feel around for equipment, while V7 stated 'why feel every dumbbell when you could just ask and have it given to you'. To similar effect, N1 explained how they disliked the confined spaces and resulting crowds in gyms, while N2 suggests increased comfort in these smaller indoor spaces.

9.2.25. Sports hall

Table 9.25 includes participants' ratings and comments for sports halls.

ID	C	Comments
V1	1	Never been to one.
V2	3	Not so keen as it is an open space with nothing to follow. I would therefore need assistance to go again.
V3	4	Some sports halls can be dim, and it may take me a few minutes to look around and get comfortable.
V4	4	Can navigate them but I find them tiring, they're big spaces often without a focus. I find myself tired of trying to lock on to what I need to look at as I'm usually looking at a wall with a variable quality light.
V5	4	Depends on what you're doing. I like swimming. I try anything and, if I like it, I'll do it.
V6	3	Swimming pools are a 4 as there's always a receptionist that will show you around, like the changing rooms. The swimming area is very familiar as it's the same colours in most places. Blue water, white tiles. Saunas and steam rooms are dark and it's not clear if other people are in there, so I can accidentally knock someone. Overall, they're generally simple environments, but leisure centres that are big can be harder such as those with bars, swimming pools, and many facilities.
V7	4	Same reasons as gyms.
V8	3	There might be an area of no obstacles in a wide-open court like tennis or cricket. I play lots of sports and so I am more confident here, and more familiar with these environments. The more you do things the more confident you get.
V9	3	Don't go, but they're going to be better than gyms because they won't have the same trip hazards.
V10	5	I'm comfortable here, I play blind tennis, but I'll have to slow down if people leave normal (non-audible) tennis balls, bags, coats, and clutter on the floor.
N1	5	Large spaces with little congestion.
N2	4	I go swimming and it first took me time to find my way from the locker to the pool. For something like tennis, it would be a 5 as you don't have to use or navigate the space. I feel more comfortable when I don't have to do something.
N3	4	They're very open spaces, but I really like to know where I am going here, and this doesn't always help.
N4	4	Unlike a gym, I know what I'm looking for in a sports hall. They're also more of an open space.
N5	4	Wouldn't bother me quite as much as a gym. They're all different, but less of working out 'where Is what' makes them better.

Table 9.25: Participants' ratings and comments for sports halls.

Sports halls were rated, on average, more positively than gyms by both VIPs and NSPs, and were particularly positively rated by VIPs relative to other environments, preceded only by private dwellings. Indeed, 6 VIPs and 1 NSP felt positively towards safety and independence in sports halls compared to only 1 VIP and 1 NSP in gyms. Similarly, 4 VIPs and 1 NSP felt negatively in this regard in gyms compared to only 1 VIP in sports halls. Infrequent use may be both a driver and result of these findings in that 2 fewer VIPs frequented gyms than sports halls.

Negative sentiment by VIPs for sports halls was for similar reason to that in gyms, but with reduced prevalence. Obstacles were an issue for 2 CVL participants in sports halls, and a B participant commented positively on the reduction in obstacles within the wider boundaries of tennis and cricket courses. However, VIPs with B, CVL, and PVL commented that the wider boundaries made using these spaces more difficult. V4 explained that they are 'big spaces without a focus', concurring with N3. Visual function particularly affected both PVL participants in that they felt that these spaces were not typically well-lit. This was also referenced by a CVL VIP, who also positively noted the usefulness of the consistent colours presented by swimming pools.

Familiarity played a role for 3 VIPs and 1 NSPs, particularly for those that actively used sports halls. However, these participants did infer that sports halls are dynamic spaces. V6 mentioned that they could not identify if people were in saunas and steam rooms, while V10 negatively described people leaving obstacles on the floor including non-audible tennis balls. 5 VIPs and 2 NSPs expressed difficulty in certain scenarios in a sports hall, a similar figure to gyms, although the more positive outlook of participants in sports halls appears to have prevailed over the issues discussed.

9.2.26. Hotel

Table 9.26 includes participants' ratings and comments for hotels.

ID	C	Comments
V1	1	Need assistance but might get used to it (would rate this a 2 if it's a small hotel).
V2	4	Could even be a 5 as I am quite happy to be there. I can take my time and find my way around, and my dog can even remember where my room is.
V3	4	My challenge is getting used to where the room is.
V4	4	Repeating issues of 'where is the number' and 'where is the sign'. Once you tune in it is ok, but numbers on lifts are an issue as they have a low contrast silver background. I typically have to bend down to read the button.
V5	4	Have had no problems. I just manage myself and ask for help when needed.
V6	4	I always go to reception, and most will help me or give me clear instructions to my room and the numbering system. Hotels with steps and different surfaces are harder to navigate but, 70% of the time, they will come with you to show you around for the first time, especially with different entry mechanisms and key lock types. Once I stay a few nights, I get used to it, and I've stayed in a lot of hotels. Cruise ships are similar, once you've been on them for a day or so you get used to them. You can't overly get lost here because you are restricted to certain areas and there are two passengers to each staff, so usually there is someone about to ask. It would be useful to have a navigation system on cruise ships because of there are so many features to visit. The hard things these days is breakfast buffets (2). They're very different in hotels and vary considerably. They're also usually understaffed so, to get help, you need to catch someone rushing out with a hot plate.
V7	4	I want to try using the Clue app where I start from where I need to start, and then I walk to my door and I use recording to retract my steps, it's breadcrumbing. I sometimes go solo to hotels, and it is all about landmarking, even with my partner. With each hotel, I knew the area of the room I liked and would always request that area.
V8	3	They are pretty good, and it is easy to get help. They guide you upstairs, and might even show you the room and what's inside if needed. I usually walk around all four walls of my room to see what's around, like a coffee table and so on. I'm usually pretty good here as their help is part of the service, like carrying my bags.
V9	2	It can be difficult and uncertain, like lifts and finding the numbers that can be small and high-up. In your room, how do some of the things work, like the TV and bathroom? Finding the right buttons can be challenging, and it's gotten harder with digital requirements such as vaccine passports on phones.
V10	4	I have a system. I go to reception, ask to be shown my room, ask for the fire evacuation plan and fire exit, the bathroom, shampoo, conditioner, climate control, phone and so on. As they take me to my room, I try and find landmarks like colours and paintings to build a route, My brain has learnt to do this and, as I walk, I project these in my mind and tick off the landmarks I need to see. I have to learn to do this in every new place.
N1	5	Easy to navigate with good signage, I've never had any issues.
N2	5	There's usually someone to guide you and tell you where things are, like the lifts and your room.
N3	5	They're usually well-set about, the story plan is easy to understand.

N4	4	It's sometimes a bit hard to find my way around. They're complex spaces but, for the most part, they're fairly well-signed.
N5	4	I quite like them. There's always a reception desk so you know there's always someone to ask, but you may be on a random floor and not know where your room is.

Table 9.26: Participants' ratings and comments for hotels.

Hotels were similarly rated to sports halls and local clinics by VIPs in that they received scores preceded only by private dwellings. An immediate observation to support this is that 8 VIPs from all groups explained that familiarity can play a positive role in hotels, and that this is often sought on arrival. V2 explain that even their guide dog can remember their room, while V7 describes how breadcrumbing smartphone applications assist them in landmarking and familiarising themselves with their space. As a result, 5 VIPs positively referenced orientation, and only 2 VIPs negatively referenced it. Other negative sentiment by VIPs pertained to signage, particularly lift button signage which was found to be small and poorly contrasting (2 responses), and hotels with steps and different ground surfaces (1 response). Technology was a barrier for 2 CVL participants where V6 experienced challenges with room entry mechanisms and lock types, and V9 with digital requirements such as vaccine passports on phones.

Assistance from staff was a prevalent coping mechanism for these VIPs, receiving 5 positive and 1 negative response. VIPs particularly described how staff would assist them in overcoming barriers, including providing clear instructions and guidance to rooms, carrying bags, and providing fire evacuation plans. 4 VIPs discussed how defined boundaries in rooms and hotels assist them; V6 felt that it was difficult to get lost in cruise ships because of being restricted to a certain area with high staff availability, and V8 walks around the boundaries of their room to understand its layout.

Subsequently, while 3 VIPs discussed some difficulty in certain scenarios, 6 VIPs expressed positive sentiment towards independence and safety within hotels, and no negative sentiment from any of the participants was recorded. NSPs delivered largely positive responses, particularly regarding signage (2 responses), staff assistance (2 responses), and layouts that were easy to understand (1 response). However, N4 and N5 did find difficulty in navigating hotels because of complex boundaries or being on a random floor without knowing room locations, respectively.

9.2.27. Additional Comments

Table 9.27 includes additional comments from participants.

ID	Comments
V1	I hold myself back because of my sight but my brother is more confident. I haven't practiced going about and meeting people, especially with the pandemic. It's hard for me to give accurate numbers because my situation is all a bit recent and so my answers are different. My hearing is also going at the same time, making everything more difficult.
V2	COVID test centres are impossible to access as a blind person as people can't help you because of distancing, and I would therefore rate them a 1.
V3	Dynamic obstacles are a challenge and frustration. For example, people leaving stuff on the floor, such as in buses.
V4	I've been a film extra. Fluorescent set signs are small banged up things that are put up right before shooting, and I have issues knowing where I need to go. I came out of London Bridge station once and knew where I should be, but relying on signage literally led to issues and getting lost as the signs assume sight of the final destination or pathway. This is the last mile navigation problem.
V5	-
V6	Popup shops are difficult because I don't know about them, so they're usually gone by the time I learn about them. Same with shops as information can be outdated.
V7	It's about mental mapping. I am fortunate that my vision has deteriorated slowly over many years, and this helped me build a mental map of London. It's important that you don't rely on one technology, but use your mind, your mouth, and your technology, such as Be My Eyes which is fantastic. There are so many free apps to try. This is the key. At sight village, a salesman was showing a magnifier to a lady, I didn't hear the cost, but he told the lady to get a loan from the bank. It really doesn't have to be so expensive.
V8	Sometimes I might have issues in local shops as they might not know me, especially when finding the entrance and exit doors.
V9	COVID test centres have been fine. They were understanding and helpful, and some used their own devices to help me fill out my forms.
V10	The hardest thing is going to countries where the letters are not English letters. They're hard to see, and not being able to ask in the language makes it impossible to get around. I can only go on foot with a GPS that speaks English. Assistance is much worse in places where visually impaired people are institutionalised, like places where disability is a taboo subject. People won't support you so well, especially when you cannot trust people.
N1	-
N2	Finding specific buildings without a map in a university campus can be impossible.
N3	I like it when I go places, but not the congestion. I'm used to nightclubs and would rate them a 5, but the issue is that it's quite easy to find the bathrooms, but not easy to actually get to them because of the congestion.
N4	I like to swim out to sea. I wear contacts but, if I go in without eye correction, then it could be hard to identify the landmarks I need to be around to navigate and get my bearings, such as finding a towel on the beach.
N5	-

Table 9.27: Participants' additional comments.

V1 described that their recently diminished sight will have affected their answers, reaffirming the difficult short-term psychological effects of sight loss that go beyond visual function. Contrastingly, V7 lost their sight over several years, and felt that they were 'fortunate' to have experienced this slower rate of reduction. V7 further reiterated the usefulness of technology, but that several tools should be used rather than sole reliance on a single one.

V2 experienced difficulties in COVID test centres given the need for distancing, and this was not considered in the prior environments. Indeed, this was seen in TfL's disruption of the TUAG service, suggesting that distancing can affect transport accessibility. However, V9 directly contradicted this by finding COVID test centres to be understanding and helpful. V3 explained that dynamic obstacles are a challenge regardless of environment, while V4 found signage to be a limiting factor in several environments, including on film sets and when navigating stations. V6 introduced the challenge of pop-up shops in that they are dynamic and may therefore close before the VIP's knowledge of them. V7 reiterated the effects of familiarity with a space through mental mapping, and V8 extended the importance of familiarity to sighted assistance in local shops (where not being known by staff caused orientation issues).

V10 reflected on mobility difficulties when visiting places with foreign languages and non-Latin alphabets, finding them hard to see, and making it 'impossible' to get around. This theme was similarly observed in responses discussing airports. Interestingly, V10 described the negative impact on sighted assistance deriving from poor equality and awareness in places where visually impaired people are institutionalised. This demonstrates the direct impact of long-term social awareness in culture on the immediate mobility of visually impaired people within these environments.

N2 stated that mapping is useful when finding their way around a university campus, while N3 found that congestion is more problematic than orientation in congested spaces such as nightclubs. Finally, N4 explained that, when swimming out to sea without contact lenses, landmark identification for orientation becomes challenging. In summary, the open-ended nature of this question limited the codability of responses as patterns and themes, as priorly demonstrated, could not be found. However, these comments remain useful in further contextualising environment-specific responses while also supporting the framework of requirements derived through this thesis. Table 9.9 includes participants' ratings and comments for taxi ranks.

9.3. Summary of Themes and Findings in Behaviours in Different Environments

The major themes obtained from the thematic analysis of all environments are divided into outdoor and indoor environments. Themes collected from outdoor environments are presented in Table 9.28.

Environment	Major Themes
Outdoor (general)	"Familiarity with the environment contributes most to confidence and perceptions of independence." "Night-time lighting conditions impact visual function and confidence." "Obstacles had an impact with building works and cycle lanes, cars and crossings posing problems."

	"Difficulties in certain spaces depend on familiarity or obstacles suggesting that difficulty is associated with reducing visual function."
Street	"Obstacles, e.g., street furniture, pose the most prevalent problems in their detection, especially the ability to detect people (acting as dynamic obstacles) even on familiar streets." "Ground conditions, particularly curbs, steps, raised pavements, and pavement width pose considerable problems for navigation." "While both technology and human assistance are useful in providing the ability to orientate, human assistance is more valuable. "
Open space (park, beach)	"Open spaces are different compared to more confined outdoor spaces such as streets as their boundaries are wider and make orientation more difficult." "Ground surfaces pose more problems than obstacles especially steps, holes, and uneven surfaces in areas including parks and beaches." "Poor lighting poses particular issues in detecting boundaries and in safe mobility." "A benefit of open spaces is the lack of congestion, though wider boundaries can be disorientating."
Shared space	"Shared spaces are, on average, the worst outdoor environment for the visually impaired individual given the dynamic nature." "Familiarity has little impact since obstacles, primarily vehicular traffic and pedestrian congestion, cannot be used as reliable landmarks." "The pain points in shared spaces are exacerbated by visual impairment." "Crowds have a positive effect in that their motion may aid the orientation of partially sighted individuals in complex spaces."
Bus stop	"Congestion at bus stops, where several buses stop behind each other, or overtake each other, is a major issue for VIPs, especially when the visual function is insufficient to detect the bus coming in time." "Sighted assistance, particularly by bus drivers, is important with a wide range of current problems inhibiting VIPs from reduced ability to hear and stop buses approaching. Unclear communications exacerbated by COVID screens." "Human assistance in bus stops is strongly correlated with not being able to identify the approaching bus, and that this is not always guaranteed, especially with several buses approaching." "Signage is often inappropriately positioned and not clearly visible to identify stops and buses."
Bus terminal	"Orientation at bus terminals, rather than obstacle avoidance or ground condition, provides major issues at bus terminals in contrast to a bus stop." "The large space of terminals together with visual aspects including signage and colour, provide different challenges for different types of visual impairment". "Human assistance is critical for the effective use of bus terminals for orientation, though this hinders independence."
Taxi rank	"VIPs can find it difficult to visually identify a taxi under certain conditions at a taxi rank."

	"An understanding of a taxi's lightning system and visually identifying if a passenger is present is needed."
Through station	"VIPs face difficult orientation issues when using through stations particularly in understanding boundaries and locations of trains and platforms." "There are numerous coping mechanisms employed by different VIP groups, ranging from sighted assistance to attempting to operate independently and using signage." "Familiarity helps in orientation, understanding the positions of obstacles (particularly platform widths), and the size of stations (bigger boundaries)." "Congestion on the whole is a challenge for VIPs, though certain VIP groups can use it to detect the direction of the escalator." "There is time pressure when finding the transport vehicle, insufficient or inaccurate temporal information and difficulties in accessing such information to determine the vehicle's departure or arrival time."
Terminating station	"While familiarity is the most important aspect for both through and terminating stations, the severity of issues in the latter are of lower magnitude." "The increase in VIP performance is due to improved orientation performance in comparison to through stations." "VIPs did not mention obstacles or ground surfaces in exit stations, given main interactions with exits rather than active platforms, thus presenting smaller risk." "VIPs eventually find an exit and use human assistance if not." "Partially sighted participants have good ability to detect exit signage which is often differently coloured and illuminated in comparison to other signage at train and underground stations."
Stadium	"Stadiums are the worst rated environment for the visually impaired as they would not go to them independently." "Sighted assistance is essential for VIPs, particularly for orientation and seat identification." "Congestion is a primary pain point leading to feelings of anxiety and 'swimming against the tide'." "Ensuring the provision of sighted assistance, clearly visible staff, and congestion management at stadiums would greatly help VIPs."

Table 9.28: Themes collected from outdoor environments.

Themes collected from indoor environments are presented in Table 9.29.

Environment	Major Themes
Indoor (general)	"In contrast to the outdoors, obstacles are of more concern to VIPs." "VIPs have a greater need for sighted assistance and/or interaction with other people compared to outdoors." "Steps pose a major problem indoors for VIPs, as does inadequate signage." "Indoor spaces, generally, require other means of mapping and orientation beyond sensory perception."
Airport	"Orientation poses a major challenge at airports given both the large boundaries and the increased number of tasks in an airport, including

	finding the entrance, check-in, the correct gate, or even sighted assistance." "Having sighted assistance and knowing where to find it is the best coping mechanism for VIPs." "Familiarity is not felt to improve performance at airports for VIPs." "While airports present an initial challenge in finding the check-in desk or sighted assistance, it gets easier after that as it becomes more chronological and controlled."
Shopping centre	"Shopping centres exhibit a mixed range of challenges for VIPs, primarily in orientation, but also in obstacles, signage, congestion, boundaries, lighting, and wayfinding technology." "The inherent complex designs and layouts of shopping centres further exacerbates these challenges and places high cognitive demands in these spaces." "These challenges are further exaggerated by the congestion and visually demanding nature of such centres, with excessive brightness, glass, and reflections as pain points". "Sighted assistance remains the primary coping mechanism but reduces feelings of independence."
Commercial unit	"VIPs perform better in such commercial units than in shopping centres as they can familiarise themselves within shops, given their smaller boundaries." "The ability to find sighted assistance in such shops is a great help for VIPs." "VIPs appear to favour and frequent local and smaller shops where staff assistance and familiarity allow for effective use of the space." "Unlike spaces with larger boundaries, obstacles in smaller spaces are less of a concern for VIPs."
Restaurant/Eatery	"Differences can be seen in how the different visual functions scored. The B and PVL group scored restaurants lower, on average, than retail units, the CVL group scored them higher." "Sighted assistance and interaction with waiting staff are by the far the most prevalent issues for VIPs". "Interaction with waiting staff is expected, though not always positive, with smaller spaces restricting the ability of staff from being able to physically assist them." "Sighted assistance can help in avoiding steps, the inability to read menus and avoiding obstacles."
Hospital	"A common complaint by VIPs is that sighted assistance at hospitals is either poor or unavailable." "Signage is a particularly challenging aspect of hospitals, together with poor contrast from uniform colours." "Familiarity in hospitals play a role in the ability of VIPs to navigate within them." "Ultimately poor signage and sighted assistance issues lead to orientation problems in hospitals, particularly in finding someone to help across entrances and different wards."
Local clinic	"Local clinics were rated substantially more highly than hospitals for a number of reasons, especially because of their smaller spaces."

	"It's much easier to obtain assistance at local clinics and orientation is much better than at hospitals." "VIPs have a high degree of familiarity with local clinics and new clinics may significantly affect their confidence."
Public house	"Public houses pose problems for the visually impaired due to their dim lighting, which exacerbates issues with obstacles and navigating around people and seats." "Assistance is valuable for orientation and finding entrances, tables, and the bar." "VIPs respond well to the independence afforded within these spaces."
Museum	"For all types of visual impairments, museums pose a range of challenges for orientation for a variety of reasons." "Boundaries were problematic in that museums are large and complex spaces requiring increased orientation effort." "Other problems include avoidance of bumping into obstacles and exhibits, compounded by poor signage and lighting." "The nature of museums requires vision to enjoy their use, and while mechanisms to cope with this appear to be available or in development, they are not consistently implemented." "Museums can reduce independence of VIPs since there is a need to attend them with others."
Theatre/Cinema	"VIPs face major problems in identifying and navigating to seats due to dim light (and poor visual function), carpeted floors and acoustics given the vast nature of the space." "Sighted assistance and the presence of others is a major positive, particularly in finding seats and navigating the space." "Other problems are congestion, arriving on time, and lack of familiarity."
Office/University building	"Such buildings typically have good lighting, no randomly placed obstacles, uniform boundaries, and provide VIPs the ability to orientate well." "There is a positive perception of independence within these spaces." "Trip hazards in such spaces are caused by randomly placed or small obstacles including bags, left items, cables, and chairs with wheels." "Among other problems faced by VIPs are poor contrast between carpets and edges, loose boundaries, and lift button visibility. These affect the ability to orientate between such spaces." "While sighted assistance is welcome, it is not always readily available or easy to find in such spaces." "The social element in these spaces is important, but VIPs worry about saying hello to the wrong person or not knowing with whom they are speaking."
Private dwelling	"Very high degree of familiarity and comfort means a high level of independence and confidence for VIPs within their homes." "There is a need to be aware of trip hazards caused by clutter, children's toys and pets." "The unique nature of such a space directly decouples visual impairment from being able to access this environment."

Gym	"Navigating gym equipment and other obstacles, including people and ground-level trip hazards, pose a problem for VIPs." "The confined nature of gyms causes crowding, and such congestion leads to navigation and safety problems." "VIPs feel intimidated and left out because of the people there, and their use of equipment in a potentially superior manner."
Sports hall	"VIPs feel their safety and independence is higher in sports halls than in gyms, given there are far fewer obstacles within the wider boundaries of tennis courts and indoor cricket nets." "Familiarity plays a major role for those who actively use sports halls, though they have to be aware of their dynamic nature."
Hotel	"VIPs' familiarity plays a positive role in orientation in hotels, and is often sought on arrival." "Challenges posed to VIPs include signage, particularly small and poorly contrasting lift button signage, hotels with steps and different ground surfaces, and technology such as room entry mechanisms and lock types." "Assistance from staff is the prevalent coping mechanism for VIPs, including assistance in overcoming barriers, providing clear instructions and guidance to rooms, carrying bags, and providing fire evacuation plans."

Table 9.29: Themes collected from indoor environments.

A substantial number of units were identified and tabulated across the qualitative data set collected to obtain these themes. This totalled 471 for the CVL group, 181 for the PVL group, 362 for the B group, 1014 for all VIPs, 324 for all NSPs, and 1338 in total for VIPs and NSPs. Given that 25 environments were included in the study, the average count for each environment was 18.8 for the CVL group, 7.2 for the PVL group, 14.5 for the B group, 40.6 for all VIPs, 13.0 for all NSPs, and 53.5 in total for VIPs and NSPs. Dividing for the size of each group to identify the average unit number identified per participant per environment yields values of 4.7 for the CVL group, 3.6 for the PVL group, 3.6 for the B group, 4.1 for all VIPs, 2.6 for all NSPs, and 3.6 in total for VIPs and NSPs.

There appears to be no correlation between average rating by participants and the codes identified within responses. The PVL group yielded the highest average scores for VIPs across environments at 3.8 yet presented the same number of units per participant per environment as the B group at 3.6. The B group yielded the lowest average scores across environments at 2.5. NSPs presented higher average scores for each environment relative to VIPs, and the higher average score across all environments relative to VIPs at 4.2. NSPs presented substantially fewer units per participant per environment than all VIPs at 2.6.

The primary limitation of this study is therefore the limited sample size, particularly in considering the types of visual impairment observed. It remains uncertain if data saturation was reached, and every challenge per environment derived. Data saturation is achieved when enough information becomes available to replicate the study without new findings, although it remains difficult to quantify (O'Reilly & Parker, 2012; Fush & Ness, 2015).

Irrespective of this limitation, a sufficient number of themes was identified for all environments to clearly distinguish unique challenges and coping mechanisms within each. This brings forward novel characteristics, particularly between NSPs, VIPs, and their subgroups.

Furthermore, the vastly differing experiences of a VIP in each environment proves the relevance and importance of this analysis. The mixed methods approach is therefore concluded successfully. Future work should address the challenges in each environment while considering and augmenting the coping mechanisms employed by its occupants.

10. Conclusions and Future Work

This chapter concludes the thesis by reflecting on its aims and objectives, summarising the relevant findings and remaining issues. The main conclusions drawn are presented in Section 10.1. Section 10.2 discusses the limitations and suggests avenues for their exploration in future work.

10.1. Conclusions

The aim of this thesis is to deliver a holistic understanding of the human, environmental, and technological factors influencing the mobility of visually impaired people. The conclusions drawn are presented in response to each relevant objective.

1. For the objective to identify the overarching process of describing visually impaired mobility (addressed in Chapter 2), the finding is that visually impaired behaviour is mesoscopic; it is dependent on individual and in-crowd operation. Moreover, the thesis defines an effective process for the analysis of mobility beginning with capacity (human factors), transitioning to performance (following environmental and technological influences), and concluding in requirements derivation and validation.

2. For the objective to gain a sufficient understanding of different visual impairments and their impacts on a person's sight (also addressed in Chapter 2), the finding is that visual impairments have varying impacts on each of the visual functions, primarily visual acuity, visual field, contrast sensitivity, and colour vision. A critical conclusion is that national standards categorise the severity of visual impairments according to reductions in different functions. As a result, their employment for participant sampling in local studies leads to incomparability in international research. The example of the British CVI is provided to demonstrate how national categorisation can vary over time.

3. In response to the objective to critically review the state-of-the-art of visually impaired mobility capacity (addressed in Chapter 3), the thesis details causal factors, and their measurement in existing medical and engineering research. This facilitates the development of a hierarchy of causal factors, comprising the most comprehensive collection of physiological and psychological factors to date. For the individual operating alone, physiological factors are found to include visual function, other sensory impairments, and the capacity to physically mobilise. Psychological factors include explicit and tacit knowledge, and short and long-term cognitive state. For the individual operating in a crowd, additional physiological factors include the capacity to detect the crowd and physical forces from the crowd. Additional psychological factors include self and social awareness.

4. Furthermore, in response to the objective above, two additional conclusions from this exercise are drawn. Firstly, current crowd dynamics research has not considered visual impairment in depth, and that the relevant mobility data is not available. Secondly, the quantification of each causal factor differs according to engineering or medical research.

Moreover, discrepancies exist within research observing the same factor, primarily in the mobility outcome measures and testing environments employed.

5. The shortcomings in (4) are addressed in Chapter 4 and 5 through an experimental methodology to collect quantitative and qualitative data on the mobility capacity of visually impaired people. This thesis specifies and implements, for the first time, an experimentation scheme or process to separate behaviours of visually impaired participants (VIPs) and normally sighted participants (NSPs) when operating individually and in a crowd. The empirical environment is capable of a wide range of data collection methods including video footage for walking time and effective speed, automated data collection for walking speed and path inefficiency, and their combination for extracting orientation errors and novel behaviours. The scheme allows self-reporting of qualitative data to correlate psychological and physiological factors.

6. From the results of the scheme in (5) above, a finding is that, operating individually, VIPs demonstrate a slower and less effective walking performance than NSPs in all environments, particularly in the introduction of larger obstacles. In crowd conditions, VIPs dominate the flow, both in its speed and safety, affecting the NSPs around them in ways not previously identified in literature. Furthermore, crowd scenarios do not necessitate a reduction in the VIP's performance compared to their individual operation. Contrarily, broad performance reductions are shown for NSPs in group, suggesting that the inverse relationship of density and speed is not reliably applicable to VIPs.

7. Also, from (5) above, it is found that restricted flows are largely preferable by participants compared to unrestricted flows. While the former presents lower walking speeds, it increases perceived safety. Unidirectional flows are the safest and most preferable of all scenarios, while opposing flows yield collisions and deadlocking. Additionally, visual, tactile, and auditory coupling between VIPs and NSPs is exhibited.

8. Another finding from (5) is that there is a positive correlation between self-reported VIP comfort and walking speed which destabilises when moving from individual to unidirectional scenarios, and completely diminishes in opposing flows. This is a profound contribution from this thesis, as existing models insufficiently associate a static reduction in walking speed to simulate a visually impaired person's behaviour relative to their normally sighted counterpart.

9. In response to the objective to critically investigate the state-of-the-art of visually impaired mobility performance, the thesis details (through literature review in Chapter 6) the environmental and technological augmentations and shortcomings. A key finding here is that visual, auditory, and tactile methods are used for environmental augmentation, although their governing standards deviate internationally. Moreover, contrast specification in British Standards is used to exemplify an incomplete translation of mobility capacity to performance. A major finding is that existing research has not systematically studied the challenges and motivations of visually impaired people in specific environments. These include bus terminals, shared spaces, university buildings, restaurants, and so forth.

10. Further to (9), a finding is that visually impaired people utilise several indoor and outdoor environments, requiring a high availability and reliability of information in each. Two primary challenges must therefore be overcome in the design of mobility aids: classification of information and ensuring its appropriate delivery. However, a consolidated framework of requirements to address these is not available in the literature. Consequently, Electronic Travel Aids (ETAs) and Electronic Orientation Aids (EOAs) cannot operate across the complete user journey, and the creation of a Binary Electronic Mobility System (BEMS) is necessitated.

11. In combining the findings above, the thesis devises a framework of user requirements for visually impaired mobility in Chapter 7. This work is informed by collaborating with WeWALK and Imperial College London in a UKRI-funded project to develop a navigation system for visually impaired people. The thesis employs the partnership's enhanced indoor positioning function, Visually Impaired Pedestrian Dead Reckoning, (VIPDR), in Chapter 8 to test with VIPs and NSPs. It is concluded that VIPDR's use of vertical acceleration for users without canes, and yaw angle for users with canes, is valid. This is particularly important as vertical acceleration is not useful for step detection in cane swing.

12. Finally, to address the literature gap in the understanding of visually impaired challenges within different environments, extensive semi-structured interviews and a thematic analysis are conducted and analysed in Chapter 9. 29 themes are listed for 25 environments encompassing challenges, motivations, and coping mechanisms for each environment. It is concluded that different environments present different challenges to the visually impaired person, and this varies according to their visual function. Therefore, a coping mechanism for one individual may not be useful for another.

In summary, the thesis fulfils its objectives and demonstrates its applicability to the lifecycle of system engineering, from requirements derivation to validation following controlled experimentation. The thesis is, therefore, successful in its aim of delivering a holistic understanding of the fundamental human, environmental, and technological factors affecting the mobility of visually impaired people.

10.2. Future Work

In achieving these aims and objectives, a number of limitations or issues remain. The following avenues are proposed for future work to address these limitations. Firstly, further work is required to exhaustively assess, in an experiment, the novelty of VIP-NSP interactions (Chapter 5). This is given the multitude of visual impairments and operational scenarios that exist. Moreover, logistical limitations in participant recruitment and clinical visual function testing hinders the depth in which speed, density, and visual function could be correlated. Statistical significance could therefore not be reached, although a high level of confidence prevails in the extensive testing of each participant.

Larger VIP and NSP sample sizes should be explored in future experimentation, particularly to determine the behaviour of VIPs with impairments not included in this instance. Clinical testing of visual function is also recommended. Moreover, the maximum group size may not have created limiting densities in all scenarios, especially in the widest section of the testing

environment. Subsequently, VIP behaviour primarily limited group performance, and the threshold for which density became the limiting factor was not found in these scenarios.

The experimentation (in Chapter 5) aimed to control as many factors as possible outside the introduction of controlled group flows. Future work should utilise these empirical findings to determine their manifestations in realistic settings. For instance, this experimentation was not able to identify how performance may change on varying the angle of opposing flows (such as the meeting of opposing groups at right-angled intersections), or from environmental augmentations and the use of different mobility aids (such as guide dogs). Indeed, variation in environmental illumination, contrast, and the introduction of auditory references such as alarms may drastically alter behaviours.

Another limitation arises in the proposal of requirements for visually impaired mobility (Chapter 7). This consolidated prior findings in the broadest set of requirements. However, these are not exhaustive, and future work should amend and expand them accordingly. This is particularly as a proportion of these requirements are contributed by prior studies, each with their own limitations. Moreover, while a subset of requirements is validated in the development of a navigation system (Chapter 8), the remainder should be adopted and validated in future work.

The experimentation conducted to validate the VIPDR component is limited in its incorporation of an ideal walking scenario (Chapter 8). Firstly, the VIP's knowledge, environmental lighting, and ground surfaces were controlled. Therefore, participants behaved at their optimal capacity, with minor fluctuations and walking errors occurring. Problematically, VIPDR's underpinning relationships of vertical acceleration and yaw angle are shown to weaken in VIPs outside their optimal behaviour. Future work should assess the validity of this positioning technique in more challenging scenarios. This should incorporate group testing which is shown to affect cane usage (Chapter 5). Thresholds at which VIPDR's underpinning relationships destabilise beyond system functionality must subsequently be found.

Another limitation in the experimentation is the sample size employed. A broad range of visual impairments is included. However, a statistically significant result could not be determined for each category of visual impairment given small subgroup sizes. This limitation is applicable to the semi-structured interviews and thematic analysis conducted with the same participant sample (Chapter 9). It is recommended that future work employs these experimental methodologies with larger participant samples. In doing so, statistical significance may arise, allowing for an exhaustive understanding of the human, environmental, and technological factors affecting the mobility of visually impaired people.

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Appendices

Appendix A – Script Verbally Delivered to Brief and Debrief Participants

Briefing Prior to Experiment

Hi everyone and thank you for joining us today to conduct this novel and exciting research. We are here to identify how people behave individually and in groups, specifically focusing on those with reduced eyesight. Before we start, please fill out the forms that we shall now hand out. These are a pre-experiment questionnaire and a consent form for your participation in this study. Please take your time to read them carefully. All the data collected today will be anonymised and stored securely. Furthermore, this data will only be used in this research, and nowhere else. We shall now enter the platform.

We are standing next to a large platform. This is where the experiment will take place. The platform has 3 sections; a straight section with no obstacles, a section with 'corridors' to walk through, and a straight section with two foam blocks positioned on the floor. There are striped black and yellow lines signalling the start and end of each section. During testing, please only walk to the end of the section you are in, and stop at this line. Please do not proceed to the next section until instructed to do so.

Firstly, our participants with a visual impairment will traverse the platform. Then, all participants, including both visually impaired participants, will traverse the platform together in a single flow. Finally, we will split you into equal groups, with a visually impaired person in each group, and position you on opposing ends of each section. More instructions will be given at each test case. All tests in groups will involve a 'restricted' and an 'unrestricted' case. In the restricted case, please attempt to maintain the same walking speed across the group, this may mean slowing down to ensure everyone remains part of the group. In the unrestricted case, you may traverse the platform at your desired pace. In both cases, everyone should attempt to traverse the platform as quickly as possible. The cases will be randomised, so please listen carefully to all instructions.

Please note that there must be absolutely no running or jogging during any of the tests. Furthermore, whilst talking is permitted during the tests, please only do so if it is necessary. It is also crucial that you do not touch or attempt to assist the visually impaired person. This includes guiding or instructing the visually impaired person. This is a fundamental part of the test, so please keep this in mind throughout the entirety of the testing.

Please join me as we now walk through the platform. Please do not hesitate to ask any questions about the platform, as we would like you to be as familiar as possible with your environment prior to testing.

**Proceed to instruct for each test case.*

Debriefing Following Experiment

That marks the end of this set of experiments. We will now hand out one last questionnaire and would greatly appreciate it if this could be filled out. Once completed, you are free to leave the testing premises unless you choose to remain for additional runs. Thank you very much for your time today.

Appendix B – VIP Questionnaire

Complete Prior to Experiment

Session ID: _____ Initials: _____ Age: _____ Gender: M / F

1) What is the diagnosis/cause of your visual impairment and do you have a CVI classification?

_____

2) How would you describe your sight in these categories? (Circle as appropriate)

Acuity (ability to read signs and text)	Poor / Fair / Good
Contrast sensitivity (ability to detect poorly lit objects)	Poor / Fair / Good
Peripheral vision (seeing objects coming from the side of your vision)	Poor / Fair / Good

3) Do you use any assistive devices? These can include glasses, canes, guide dogs, voice-over software and screen-readers.

_____

4) Please provide any additional details on your visual impairment

_____

5) Have you ever participated in an evacuation (such as a fire drill?)	Yes / No
If so, have you ever felt unsafe or unable to evacuate?	Yes / No

Please provide additional details as to why this is:

_____

Complete Following Experiment

The platform is defined as Section 1: No obstacles, Section 2: Corridors, Section 3: Foam steps

Please rate your comfort in each scenario on a scale of (1) to (5), where (1) is least comfort and (5) is the most.

1) Individually:	Comfort
Section 1	1 / 2 / 3 / 4 / 5
Section 2	1 / 2 / 3 / 4 / 5
Section 3	1 / 2 / 3 / 4 / 5
2) In the unrestricted single flow:	**Comfort**
Section 1	1 / 2 / 3 / 4 / 5
Section 2	1 / 2 / 3 / 4 / 5
Section 3	1 / 2 / 3 / 4 / 5
3) In the unrestricted opposing flow:	**Comfort**
Section 1	1 / 2 / 3 / 4 / 5
Section 2	1 / 2 / 3 / 4 / 5

Section 3 1 / 2 / 3 / 4 / 5

4) When traversing the platform, please rank the following on a scale of (1) to (5), where (1) was the least comfortable scenario, and (5) was the most comfortable scenario.

Individually _____

In a restricted single group flow _____

In an unrestricted single group flow _____

In a restricted opposing group flow _____

In an unrestricted opposing group flow _____

5) Did you feel that the presence of normally sighted people on the platform affected your actions during the experiment? Yes / No

If so, how, and why was this?

_____

5) Did you feel that the presence of another visually impaired person on the platform (if applicable) affected your actions during the experiment? Yes / No

If so, how, and why was this?

_____

Appendix C – NSP Questionnaire

Complete Prior to Experiment

Session ID: _____ Initials: _____ Age: _____ Gender: M / F

1) Have you ever participated in an evacuation (such as a fire drill?) Yes / No

If so, have you ever felt unsafe or unable to evacuate? Yes / No

Please provide additional details as to why this is:

_____

Complete Following Experiment

The platform is defined as Section 1: No obstacles, Section 2: Corridors, Section 3: Foam steps

Please rate your comfort in each scenario on a scale of (1) to (5), where (1) is the least comfort and (5) is the most comfort.

1) In the unrestricted single flow: Comfort

Section 1 1 / 2 / 3 / 4 / 5

Section 2 1 / 2 / 3 / 4 / 5

Section 3 1 / 2 / 3 / 4 / 5

2) In the unrestricted opposing flow: Comfort

Section 1 1 / 2 / 3 / 4 / 5

Section 2 1 / 2 / 3 / 4 / 5

Section 3 1 / 2 / 3 / 4 / 5

3) When traversing the platform, please rank the following on a scale of (1) to (5), where (1) was the least comfortable scenario, and (5) was the most comfortable scenario.

In a restricted single group flow _____

In an unrestricted single group flow _____

In a restricted opposing group flow _____

In an unrestricted opposing group flow _____

4) Did you feel that the presence of visually impaired persons on the platform affected your actions during the experiments? Yes / No

If so, how, and why was this?

_____

Appendix D – VIP and NSP Additional Preliminary Information

Table D1: VIP additional preliminary information

VIP	Participated in Evacuation	Felt Unsafe
A1	Yes	No
A2	Yes	No
B1	Yes	No
B2	Yes	No
C1	No	N/A
C2	No	N/A
D1	Yes	Yes
E1	No	N/A
E2	Yes	Yes, I was with friends at the cinema in a shopping complex with a very loud alarm and announcements. People were rushing and pushing, it was scary, and I tried to stay near the wall and edges.
F1	No	N/A
G1	No	N/A
H1	Yes	No, it was in a known place, and I always ask for the evacuation route, I don't go alone and am always aware.

Table D2: NSP additional preliminary information

ID	Participated in Evacuation	Felt Unsafe
AN1	Yes	No
AN2	Yes	No
AN3	Yes	No
AN4	Yes	No
AN5	Yes	Yes, I used to live in top floor flat, running down the stairs with lots of people at the same time is unsafe
AN6	Yes	Yes, old school fire doors were shut due to electricity being disconnected teachers had to use a key to unlock which took a while
AN7	No	N/A
AN8	Yes	No
AN9	No	N/A
AN10	Yes	No
AN11	Yes	No
BN1	Yes	No
BN2	Yes	No
BN3	Yes	No
BN4	Yes	No
CN1	No	N/A

CN2	Yes	No
CN3	Yes	No
CN4	Yes	No
CN5	No	N/A
DN1	Yes	No
DN2	No	N/A
EN1	Yes	No
EN2	Yes	No
EN3	No	N/A
EN4	Yes	No
EN5	Yes	No
EN6	Yes	Yes, no one knew where to go
EN7	Yes	No
EN8	Yes	No
EN9	Yes	No
EN10	Yes	No
EN11	Yes	No
GN1	No	N/A
GN2	Yes	No
GN3	Yes	No
GN4	Yes	No
GN5	No	N/A
HN1	Yes	No
HN2	Yes	No
HN3	Yes	No
HN4	Yes	No
HN5	No	N/A
HN6	Yes	No
HN7	Yes	No
HN8	No	N/A
IN1	Yes	No
IN2	Yes	No
IN3	Yes	No

Table E1: Pass 1, Pass 2, Average Pass Time ('Baseline' in later tables), and Percentage Change in Pass Time for each VIP walking individually through each section

VIP	Section 1				Section 2				Section 3			
	Pass 1 Time [s]	Pass 2 Time [s]	Avg. Pass Time [s]	ΔPass [%]	Pass 1 Time [s]	Pass 2 Time [s]	Avg. Pass Time [s]	ΔPass [%]	Pass 1 Time [s]	Pass 2 Time [s]	Avg. Pass Time [s]	ΔPass [%]
A1	4.0	3.7	3.9	-7.5	6.6	5.3	6.0	-19.7	6.2	6.0	6.1	-3.2
A2	19.8	16.2	18.0	-18.4	30.6	26.0	28.3	-15.0	20.6	19.3	20.0	-6.3
B1	8.9	8.6	8.8	-3.4	22.7	22.1	22.4	-2.4	13.4	14.6	14.0	9.0
B2	11.9	11.0	11.5	-7.6	43.1	33.6	38.4	-22.0	19.5	18.3	18.9	-6.2
C1	10.7	10.9	10.8	1.9	23.0	16.7	19.9	-27.4	17.6	11.9	14.8	-32.4
C2	22.7	10.9	16.8	-52.0	48.1	31.4	39.8	-34.7	29.3	23.6	26.5	-19.5
D1	13.0	7.8	10.4	-40.0	19.1	16.0	17.6	-16.2	17.6	15.5	16.6	-11.9
E1	13.4	10.0	11.7	-25.4	23.6	18.7	21.2	-20.8	17.2	14.2	15.7	-17.4
E2	10.8	11.1	11.0	2.8	18.6	18.2	18.4	-2.2	18.7	15.2	17.0	-18.7
F1	25.1	17.8	21.5	-29.1	38.6	18.9	28.8	-51.0	23.5	19.0	21.3	-19.1
G1	6.2	5.9	6.0	-4.1	9.2	8.6	8.9	-6.5	13.3	8.4	10.9	-36.8
H1	6.2	6.0	6.1	-3.2	7.3	7.5	7.4	2.7	9.6	7.2	8.4	-25.0
Avg.	12.7	10.0	11.4	-15.5	24.2	18.6	21.4	-17.9	17.2	14.4	15.8	-15.6
Avg. -H1	13.3	10.4	11.8	-16.6	25.7	19.6	22.7	-19.8	17.9	15.1	16.5	-14.8

Table E2: Pass 1, Pass 2, Average Pass Time ('Baseline' in later tables), and Percentage Change in Pass Time for each NSP walking individually through each section

VIP	Section 1				Section 2				Section 3			
	Pass 1 Time [s]	Pass 2 Time [s]	Avg. Pass Time [s]	ΔPass [%]	Pass 1 Time [s]	Pass 2 Time [s]	Avg. Pass Time [s]	ΔPass [%]	Pass 1 Time [s]	Pass 2 Time [s]	Avg. Pass Time [s]	ΔPass [%]
FN2	5.9	6.3	6.1	6.8	8.2	8.0	8.1	-2.4	6.5	6.6	6.6	1.5
GN2	6.4	6.9	6.7	7.8	6.9	7.5	7.2	8.7	7.3	6.5	6.9	-11.0
HN2	5.8	5.6	5.7	-3.4	5.3	5.9	5.6	11.3	6.0	5.9	6.0	-1.7
IN1	7.5	7.5	7.5	0.0	8.4	8.8	8.6	4.8	6.0	7.2	6.6	20.0
IN2	6.9	7.1	7.0	2.9	8.9	9.0	9.0	1.1	7.7	8.3	8.0	7.8
Avg.	6.5	6.7	6.6	2.8	7.5	7.8	7.7	4.7	6.7	6.9	6.8	3.3

Table E3: Average, standard deviation, and coeff. of variation for baseline of all VIPs

All VIPs	Section 1	Section 2	Section 3
Avg. (s)	11.4	21.4	15.8
SD (s)	5.2	11.1	5.6
CV (%)	45.7	51.7	35.6

Table E4: Average, standard deviation, and coeff. of variation for baseline of all VIPs excluding H1

All VIPs (-H1)	Section 1	Section 2	Section 3
Avg. (s)	11.8	22.7	16.5
SD (s)	5.2	10.6	5.4
CV (%)	43.6	46.9	32.6

Table E5: Average, standard deviation, and coeff. of variation for baseline of all NSPs

All VIPs	Section 1	Section 2	Section 3
Avg. (s)	6.6	7.7	6.8
SD (s)	0.7	1.3	0.8
CV (%)	10.8	17.4	11.1

Appendix F – VIP in Unidirectional Crowd Flow Results

Table F1: Unrestricted unidirectional flow times and percentage change relative to baseline

VIP	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
A1	5.2	35.1	6.8	14.3	5.4	-11.5
A2	15.8	-12.1	31.3	10.6	17.3	-13.3
B1	12.9	47.4	20.7	-7.5	16.3	16.4
B2	14.8	29.3	24.6	-35.9	12.6	-33.3
C1	14.5	34.3	18.4	-7.3	14.4	-2.4
C2	14.9	-11.3	39.9	0.4	19.5	-26.3
D1	11.0	5.8	14.2	-19.1	14.0	-15.4
E1	7.4	-36.8	17.4	-17.7	11.2	-28.7
E2	7.3	-33.3	10.2	-44.6	8.7	-48.7
F1	13.3	-38.0	31.2	8.5	14.0	-34.1
G1	5.3	-12.0	6.8	-23.6	7.0	-35.5
H1	4.0	-34.4	7.4	0.0	8.3	-1.2
Avg.	10.5	-2.2	19.1	-10.2	12.4	-19.5
Avg. -H1	11.1	0.8	20.1	-11.1	12.8	-21.2

Table F2: Restricted unidirectional flow times and percentage change relative to baseline

VIP	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
A1	10.0	159.7	10.5	76.5	6.3	3.3
A2	18.9	5.2	30.0	6.0	16.4	-17.8
B1	14.6	66.9	24.1	7.8	25.3	80.7
B2	13.0	13.5	32.6	-15.0	18.0	-4.8
C1	9.2	-14.8	22.0	10.8	14.6	-1.0
C2	17.6	4.8	36.9	-7.2	24.1	-8.9
D1	14.5	39.4	20.9	19.1	17.3	4.5
E1	10.6	-9.4	29.0	37.1	11.9	-24.2
E2	8.1	-26.0	9.6	-47.8	8.5	-49.9
F1	18.8	-12.4	23.7	-17.6	14.1	-33.7
G1	5.5	-8.7	8.4	-5.6	6.2	-42.9
H1	5.5	-9.8	10.0	35.1	8.6	2.4
Avg.	12.2	17.4	21.5	8.3	14.3	-7.7
Avg. -H1	12.8	19.8	22.5	5.8	14.8	-8.6

Table F3: Average, standard deviation, and coeff. of variation for all unidirectional flows

All VIPs	**Section 1**		**Section 2**		**Section 3**	
	Unrest.	Rest.	Unrest.	Rest.	Unrest.	Rest.
Avg. (s)	10.5	12.2	19.1	21.5	12.4	14.3
SD (s)	4.4	4.8	10.9	9.9	4.4	6.4
CV (%)	41.8	39.3	57.1	45.9	35.2	44.6

Table F4: Average, standard deviation, and coeff. of variation for all unidirectional flows excluding VIP H1

All VIPs (-H1)	**Section 1**		**Section 2**		**Section 3**	
	Unrest.	Rest.	Unrest.	Rest.	Unrest.	Rest.
Avg. (s)	11.1	12.8	20.1	22.5	12.8	14.8
SD (s)	4.1	4.5	10.8	9.6	4.4	6.4
CV (%)	36.7	35.2	53.4	42.7	34.2	43.3

Appendix G – VIP in Opposing Crowd Flow Results

Table G1: Unrestricted opposing flow times and percentage change relative to baseline

ID	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
A1	8.8	128.6	9.0	51.3	7.7	26.2
A2	17.3	-3.8	26.9	-5.0	19.1	-4.3
B1	15.4	76.0	29.0	29.7	18.7	33.6
B2	10.5	-8.3	18.9	-50.7	10.6	-43.9
C1	13.2	22.2	19.9	0.3	13.2	-10.5
C2	13.8	-17.9	35.0	-12.0	12.4	-53.1
D1	12.8	23.1	14.6	-16.8	15.0	-9.4
E1	11.2	-4.3	19.2	-9.2	12.0	-23.6
E2	9.7	-11.4	14.6	-20.7	9.8	-42.2
F1	11.6	-45.9	21.8	-24.2	13.8	-35.1
G1	6.6	9.5	10.3	15.7	8.4	-22.6
Avg,	11.9	15.3	19.9	-3.8	12.8	-16.8

Table G2: Restricted opposing flow times and percentage change relative to baseline

ID	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
A1	17.2	346.8	19.1	221.0	10.8	77.1
A2	20.8	15.7	30.1	6.4	22.7	13.8
B1	16.6	89.7	20.9	-6.6	23.2	65.7
B2	15.6	36.2	30.0	-21.8	14.3	-24.3
C1	11.9	10.2	18.9	-4.8	14.8	0.3
C2	13.2	-21.4	29.9	-24.8	18.1	-31.6
D1	13.5	29.8	20.4	16.2	18.7	13.0
E1	9.6	-18.0	20.1	-5.0	10.5	-33.1
E2	8.9	-18.7	15.3	-16.9	9.5	-44.0
F1	16.5	-23.1	25.0	-13.0	14.4	-32.2
G1	7.4	22.8	11.3	27.0	8.0	-26.3
Avg.	13.7	42.7	21.9	16.2	15.0	-2.0

Table G3: Average, standard deviation, and coeff. of variation for all opposing flows

All VIPs	Section 1		Section 2		Section 3	
	Unrest.	Rest.	Unrest.	Rest.	Unrest.	Rest.
Avg. (s)	11.9	13.7	19.9	21.9	12.8	15.0
SD (s)	3.0	4.1	8.0	6.2	3.7	5.2
CV (%)	25.6	29.6	39.9	28.3	29.3	34.5

Table H1: Unrestricted unidirectional flow time and percentage change relative to baseline for H1 positioned at the rear of a group of NSPs

ID	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
H1	4.7	-23.0%	6.3	-14.9	5.1	-39.3

Table H2: Restricted unidirectional flow time and percentage change relative to baseline for H1 positioned at the rear of a group of NSPs

ID	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
H1	4.6	-24.6	7.1	-4.1	6.1	-27.4

Table H3: Unrestricted opposing flow times and percentage change relative to baseline for H1 and HN2 in different formations

ID	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
H1 in group against only HN2						
H1	5.2	-14.8	7.9	6.8	5.8	-31.0
HN2	7.2	26.3	6.9	23.2	5.6	-6.7
HN2 in group against only H1						
H1	5.3	-13.1	6.6	-10.8	5.7	-32.1
HN2	7.6	33.3	8.8	57.1	5.9	-1.7

Table H4: Restricted opposing flow times and percentage change relative to baseline for H1 and HN2 in different formations

ID	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
H1 in group against only HN2						
H1	6.6	8.2	9.2	24.3	7.9	-6.0
HN2	6.0	5.3	10.1	80.4	6.7	11.7
HN2 in group against only H1						
H1	6.0	-1.6	7.4	0.0	7.0	-16.7
HN2	6.2	8.8	11.3	101.8	7.4	23.3

Table H5: Unrestricted opposing flow times and percentage change relative to baseline for IN1 and IN2 in different formations

ID	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
IN1 in group against only IN2						
IN1	4.8	-36.0	8.3	-3.5	4.6	-30.3
IN2	6.2	-11.4	9.8	9.5	6.1	-23.8
IN1 and IN2 in equal opposing groups						
IN1	5.7	-24.0	6.6	-23.3	4.6	-30.3
IN2	5.8	-17.1	8.0	-10.6	5.5	-31.3

Table H6: Restricted opposing flow times and percentage change relative to baseline for IN1 and IN2 in different formations

ID	Section 1		Section 2		Section 3	
	Time [s]	Change [%]	Time [s]	Change [%]	Time [s]	Change [%]
IN1 in group against only IN2						
IN1	8.3	10.7	9.8	14.0	7.2	9.1
IN2	9.7	38.6	9.0	0.6	7.1	-11.3
IN1 and IN2 in equal opposing groups						
IN1	8.8	17.3	9.8	14.0	8.9	34.8
IN2	8.6	22.9	9.6	7.3	7.8	-2.5

Table H7: Opposing flow times and percentage changes between the unrestricted and restricted condition for session J

ID	Section 1			Section 2			Section 3		
	Unres. (s)	Res. (s)	Change [%]	Unres. (s)	Res. (s)	Change [%]	Unres. (s)	Res. (s)	Change [%]
Pass 1									
J1	7.7	13.9	80.5	7.1	8.7	22.5	5.5	9.6	74.5
J2	7.1	15.4	116.9	6.9	10.8	56.5	5.6	9.0	60.7
Pass 2									
J1	5.5	12.8	132.7	6.4	8.0	25.0	4.5	8.2	82.2
J2	5.3	6.0	13.2	6.1	6.2	1.6	5.4	7.1	31.5

Appendix I – VIP Post-Experiment Questionnaire Results

Table I1: The comfort levels each VIP experienced individually, in unrestricted unidirectional flows, and in unrestricted opposing flows, where one is least comfortable and five is the most comfortable

ID	Individual comfort			Unrest. uni. flow comfort			Rest. opp. flow comfort		
	Sec. 1	Sec. 2	Sec. 3	Sec. 1	Sec. 2	Sec. 3	Sec. 1	Sec. 2	Sec. 3
A1	5	5	5	4	4	4	3	3	3
A2	3	3	3	4	4	4	4	4	4
B1	5	4	3	4	4	4	3	3	3
B2	4	2	4	5	4	5	5	4	5
C1	4	4	3	4	4	4	4	4	4
C2	3	3	3	3	3	3	2	2	2
D1	4	4	3	4	3	3	3	4	4
E1	4	3	4	3	3	4	2	2	3
E2	3	2	2	4	4	4	4	1	3
F1	3	2	2	2	1	1	1	1	1
G1	5	5	5	5	5	5	3	3	3
H1	5	5	4	5	5	4	5	5	4

Table I2: VIPs' ranking of the different types of passes relative to one another where one is least comfortable and five is the most comfortable

ID	Individual	Rest. uni. flow	Unrest. uni. flow	Rest. opp. flow	Unrest. opp. flow
A1	5	4	4	3	2
A2	5	5	5	5	5
B1	3	5	4	2	1
B2	1	2	3	4	5
C1	1	4	5	3	2
C2	3	4	5	2	1
D1	5	4	3	2	1
E1	5	4	3	2	1
E2	3	3	3	1	1
F1	5	4	3	2	1
G1	5	4	3	2	1
H1	1	5	4	3	2

Table I3: VIPs' sentiment towards other NSPs and VIPs on the platform

ID	Did the presence of NSPs on the platform impact your actions?	Did the presence of the other VIP on the platform impact your actions?
A1	No	Yes, I avoided them and gave them priority
A2	Yes	No
B1	Yes, felt more protected	Yes, expected that there was another VIP there so took more care
B2	No	Yes, took more notice to make sure I avoided them. I had to be comfortable with my speed to make sure I was safe
C1	Yes, used them as a guide even when they were not there	No
C2	Yes, going in the same direction helps, but opposing flow made it harder	Yes, made me much more aware, especially if they were going to collide
D1	Yes, I followed people and kept with their speed, slowing down when they do and vice versa	N/A
E1	Yes, much more confident as you have someone to bail you out	Yes, scared to bump into them so more apprehensive
E2	Yes, they were useful to follow, especially in the second section of zig zags and third with steps	Yes, you could hear their cane which was useful, but when we were straight ahead, I did not want to push them to the side otherwise they might lose concentration
F1	Yes, sighted people walked wherever they wanted, so it made it uncomfortable	N/A
G1	No, did not know if they were VIP or not so made no difference	N/A
H1	Yes, when people were coming towards me in group, it was easier. I was worried of hitting people with a cane, or them going the wrong way and following them. I would listen to people to help move around, but if an alarm was on it would have been different. I would follow people's shoulders, and this is better when in a group as I can follow the flow and people more often. If people are coming at me, I look straight at them to let them know my intention, but to see them I have to look down at 4 o'clock to use acentric viewing. I wouldn't use a cane if I knew the environment, and I'd therefore be slower in an evacuation as I most likely wouldn't use my cane	N/A

Figure I1: VIPs' unidirectional flow comfort levels across the different sections

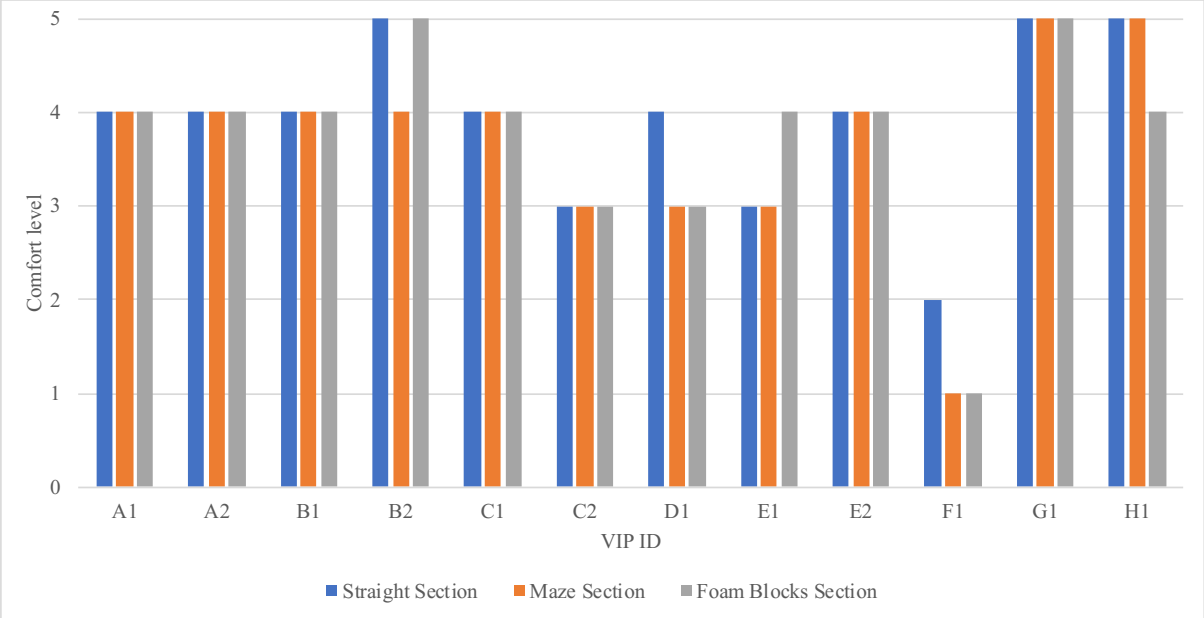


Figure I2: VIPs' opposing flow comfort levels across the different sections

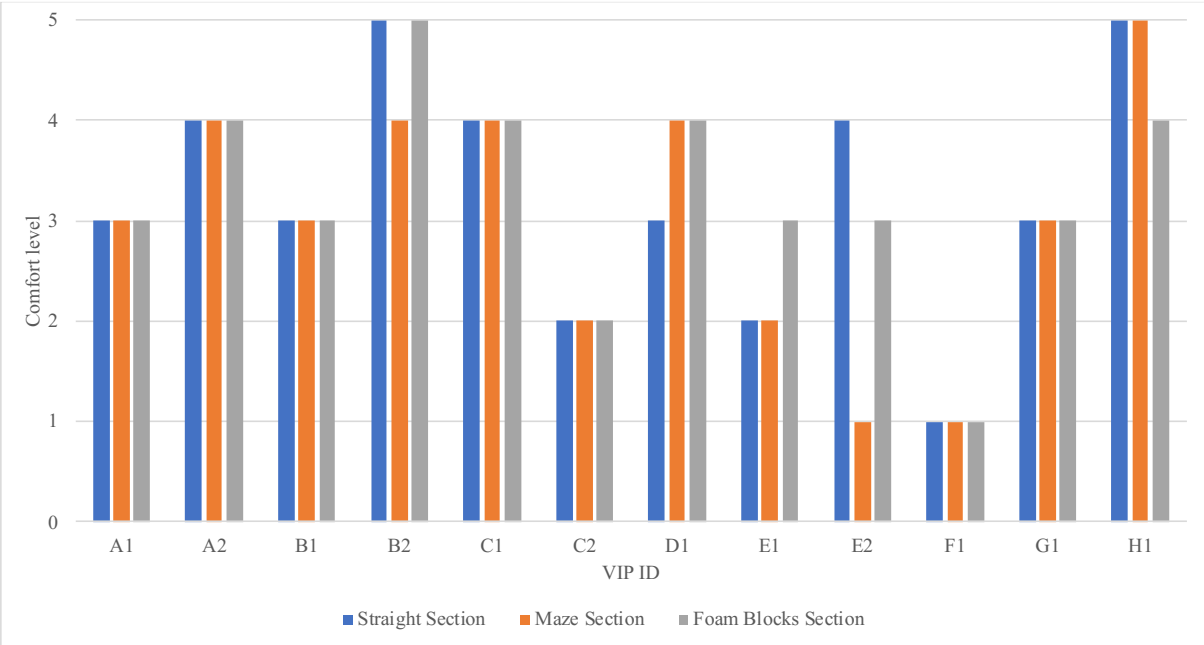


Figure I3: VIPs' ranking of the different types of passes

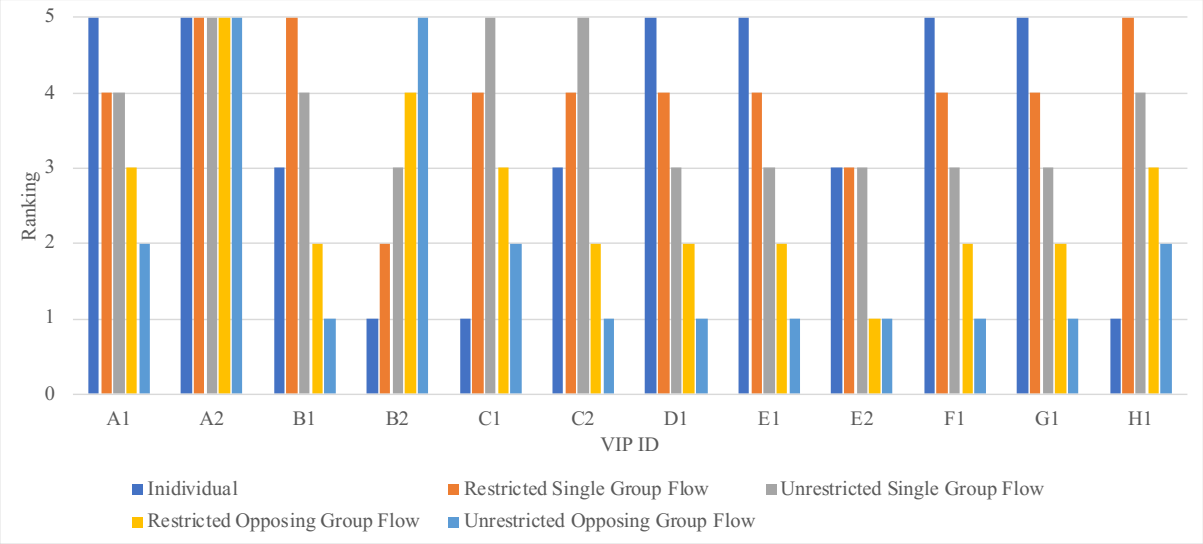


Table J1: The comfort levels each NSP experienced in unrestricted unidirectional flows and unrestricted opposing flows, where one is least comfortable and five is the most comfortable

ID	Unrest. uni. flow comfort			Unrest. opp. flow comfort		
	Section 1	Section 2	Section 3	Section 1	Section 2	Section 3
AN1	5	4	5	3	2	4
AN2	3	2	5	2	3	4
AN3	3	2	5	2	1	5
AN4	5	4	4	2	3	4
AN5	5	3	4	4	3	3
AN6	5	4	5	2	3	3
AN7	4	5	4	3	4	3
AN8	4	3	5	3	2	4
AN9	4	3	3	3	1	2
AN10	2	3	4	1	2	4
AN11	5	4	5	4	3	4
BN1	5	5	5	5	4	5
BN2	5	4	5	4	3	4
BN3	4	3	5	3	2	4
BN4	3	3	4	3	1	3
CN1	4	4	4	3	4	3
CN2	4	3	3	3	2	2
CN3	3	4	3	3	4	4
CN4	3	5	5	4	5	5
CN5	4	3	3	3	2	2
DN1	5	4	2	1	2	5
DN2	N/A	N/A	N/A	3	1	5
EN1	5	4	4	3	2	3
EN2	5	3	4	3	1	2
EN3	4	4	5	4	3	5
EN4	5	4	4	3	2	2
EN5	5	5	5	5	3	4
EN6	4	3	4	3	2	3
EN7	5	4	5	2	1	1
EN8	4	2	4	3	2	3
EN9	5	3	4	5	3	4
EN10	4	4	4	4	4	3
EN11	5	5	5	5	5	5
GN1	4	3	3	3	3	3
GN2	4	3	3	3	2	2
GN3	5	4	5	4	4	4
GN4	5	5	4	5	4	3
GN5	3	4	3	3	3	3

HN1	5	4	5	4	2	4
HN2	4	3	3	3	2	3
HN3	5	5	5	3	2	3
HN4	4	4	4	3	2	4
HN5	3	2	2	3	2	2
HN6	N/A	N/A	N/A	3	1	1
HN7	4	4	4	4	3	3
HN8	4	4	4	4	4	4
IN1	N/A	N/A	N/A	5	4	5
IN2	N/A	N/A	N/A	5	4	4
IN3	N/A	N/A	N/A	5	4	5

Table J2: NSPs' ranking of the different types of passes relative to one another where one is least comfortable and five is the most comfortable

ID	Rest. uni. flow	Unrest. uni. flow	Rest. opp. flow	Unrest. opp. flow
AN1	5	4	4	3
AN2	4	5	3	2
AN3	3	4	2	3
AN4	5	4	3	2
AN5	4	3	1	2
AN6	4	5	3	2
AN7	2	3	2	3
AN8	4	5	3	2
AN9	4	3	2	1
AN10	3	4	1	2
AN11	5	4	3	2
BN1	5	5	5	5
BN2	4	5	2	3
BN3	5	4	3	2
BN4	4	3	4	3
CN1	4	3	3	3
CN2	3	4	2	3
CN3	5	4	4	4
CN4	5	4	5	4
CN5	3	4	2	3
DN1	4	4	3	4
DN2	N/A	N/A	3	5
EN1	5	4	3	2
EN2	5	3	3	2
EN3	5	4	4	3
EN4	5	4	4	3
EN5	4	5	3	4
EN6	4	3	4	3
EN7	5	4	3	1

EN8	5	5	3	1
EN9	4	4	5	1
EN10	4	3	3	3
EN11	5	4	5	4
GN1	4	4	3	3
GN2	4	3	2	1
GN3	5	5	3	4
GN4	5	4	2	3
GN5	2	3	3	4
HN1	3	4	2	1
HN2	4	3	4	3
HN3	N/A	3	2	1
HN4	5	4	4	2
HN5	3	2	3	2
HN6	N/A	N/A	N/A	N/A
HN7	4	4	2	3
HN8	3	4	3	4
IN1	N/A	N/A	2	1
IN2	N/A	N/A	4	4
IN3	N/A	N/A	5	4

Table J3: NSPs' sentiment towards other VIPs on the platform

ID	Did the presence of VIPs on the platform impact your actions?
AN1	Yes, there was a balance between trying to save yourself and at the same time being polite and not interfering with the VIP. I would feel more ok bumping into a non-VIP than a VIP so their presence made me more hesitant
AN2	Yes, slower pace in restricted scenarios, more potential for collision in opposing scenarios
AN3	Yes, in restricted flow, the average speed was slowed. In unrestricted flow, especially in section 2 the space is further limited by the movement of Vip
AN4	Yes, a little bit as seeing the cane sweeping in front meant there was an area in front of them that I had to be weary of
AN5	Yes, had to be careful not to walk in their way, was worried they might get pushed over
AN6	Yes, it was difficult to overtake them as they were slower and moving non-uniformily
AN7	Yes, especially in the single flow, the group needs to move according to the VIP
AN8	Yes, slower pace and need to look out for the cane
AN9	Yes
AN10	Yes, it caused me to slow down and stay behind them or avoid bumping into them. I was aware of their presence and was very conscious of bumping into them and wanted to get out their way
AN11	Yes, It was necessary to manoeuvre around the VIP as they were moving more slowly
BN1	No
BN2	Yes, the VIP were a slow-moving obstacle relative to the non-impaired

BN3	Yes, collisions with opposing VIP, stumbling over VIP in my group, moved slower around them as unpredictable where they may step or move cane, desired to avoid collisions
BN4	Yes, in real life I would stop to help, and it was difficult to overcome the urge. Ignoring this, the presence of the VIP disrupted the flow of the crowd, especially in the maze. At one point I was close to tripping over a white cane. I moved more slowly overall than I would have if the VIP was not present, even in the unrestricted flow
CN1	Yes
CN2	Yes, be wary about her presence, meaning my behaviour during the evacuation is changed. Although I didn't feel like it is an emergency evacuation scenario, so I was not behaving the same way as if I was in an emergency evacuation
CN3	Yes, affected how fast or slow my walking was and when to avoid obstacles. Also, unsure when or if I should help the VIP
CN4	Yes, I felt I needed to be more careful when walking by or along the VIP. I was trying not to block their way, slowing my speed down and not trying to squeeze or overtake
CN5	Yes, it was hard to navigate them in the flow. It was hard to go through with them
DN1	No
DN2	No
EN1	Yes, was more aware of whether I should overtake or not. Walked less aggressively. Maybe slightly slower when 'trapped behind' VIP
EN2	Yes, I was more likely to overtake someone without an impairment, and more likely to let a VIP to go ahead of me
EN3	Yes, I felt I was more aware of them and needed to give them more space than another person because I didn't want to cause them additional stress
EN4	Yes, concern for bumping into them, didn't want to get in their way
EN5	Yes, didn't want to impede them, wasn't sure whether to help them
EN6	Yes, we will tend to walk carefully and slower, in order not to bump into the VIP
EN7	Yes, I was nervous of bumping into them/tripping on a stick. Was more reluctant to walk at high speed towards them. Was more affected by the VIP walking towards me as opposed to them walking with me in the same direction
EN8	Yes, the sweeping area of the walking stick prevented overtaking. In opposing flow, we tended to stick to one side to avoid conflict. Which side this was tended to be determined by where the VIP was, as they were less likely to see where the opposing flow was
EN9	Yes, in an unrestricted flow, it is hard to overtake and the walking stick will block my route
EN10	No
EN11	Yes, I notice the VIP was struggling a little bit, wasn't sure whether I should help or continue
GN1	Yes, my human values and morals did not allow me to overtake him/push him out of the way
GN2	Yes, I would sometimes turn back to check on the VIP, as I would do in real life. I tried to avoid this in general, however
GN3	Yes, As I was conscious that there was a VIP, I was more careful, but in real life situations, most people, including myself, would not be aware unless it was pointed out
GN4	No

GN5	No
HN1	Yes, if I know a VIP was behind me, I wanted to walk a bit faster to avoid being hit by the cane
HN2	Yes, I would be aware of the VIP and try to guess where they were headed, so I wouldn't get in their way
HN3	Yes, this VIP could not see me so I have to avoid her at short notice
HN4	Yes, had to mind the stick, hitting the back of your shoes, you might have to give away at choke points (momentarily stop)
HN5	Yes, with the cane in front of us, a person becomes bigger almost as you are trying to avoid getting hit/tripped by the cane as well as the VIP
HN6	N/A
HN7	Yes, needed to be aware of the cane, so had to look around more often
HN8	N/A
IN1	N/A
IN2	N/A
IN3	N/A

Table K1: Session J NSP preliminary information

ID	Age	Gender	Participated in Evacuation	Felt Unsafe
JN1	20	M	Yes	No
JN2	24	M	No	N/A
JN3	34	M	No	N/A
JN4	21	M	Yes	No
JN5	23	M	Yes	No
JN6	18	M	Yes	No
JN7	33	M	Yes	No
JN8	35	M	No	N/A
JN9	21	M	Yes	Yes, felt trapped
JN10	23	M	Yes	No
JN11	23	M	Yes	No
JN12	22	M	Yes	No

Table K2: The comfort levels each NSP experienced in the unrestricted opposing flows, where one is least comfortable and five is the most comfortable

ID	Section 1	Section 2	Section 3
JN1	4	2	3
JN2	2	1	4
JN3	2	2	2
JN4	5	3	5
JN5	2	2	4
JN6	2	3	4
JN7	2	4	2
JN8	2	2	3
JN9	4	3	2
JN10	1	2	3
JN11	3	4	5
JN12	4	4	4

Table K3: NSPs' ranking of the different types of opposing passes relative to one another where one is least comfortable and five is the most comfortable

ID	Rest. opp. flow	Unrest. opp. flow
JN1	5	2
JN2	4	2
JN3	3	2
JN4	1	2
JN5	4	2
JN6	3	2
JN7	2	1
JN8	3	2
JN9	4	1

JN10	3	2
JN11	2	1
JN12	4	4

Appendix L – Pozyx Data Extraction Code (MATLAB)

```
% Investigating and Comparing the Behaviour of Visually Impaired People in
% Unidirectional and Opposing Crowd Flows
% Pozyx Data Extraction Code - Jean Marc Feghali - V1.1 (11/09/22)

clc; close all; clear all;
datafull = readtable('Calibration.csv'); % Read file

%% User Inputs

% Input required time interval in format (t1 = start, t2 = end)
t1 = 0;
t2 = 1;

% Input required tag number (VIP 1: 17883, VIP 2: 7448)
inputtag = 17883;
% Input path length (either 9.6 m or 11 m according to section, or 60.4 m total)
pathlength = 60.4;
% Input max uncertainty tolerance from Pozyx raw data
maxuncertainty = 150; % higher is more error tolerance - 150 recommended
% Input desired smoothing for move median
smoothcoords = 30; % higher is smoother - 30 recommended
smoothspeed = 70; % higher is smoother - 70 recommended

%% Prepare Data

% Initialise scalars to align timestamps
inputtime = [t1 t2];
duration = t2 - t1;
s = inputtime(:, 1);
e = inputtime(:, 2);
% Initialise timestamp
timeall = datafull(:, "timestamp");
% Initialise Success
successall = datafull(:, "success");
% Initialise Uncertainty
uncertaintyall = datafull(:, "data__metrics__reliability__uncertainty");
% Initialise Tag
tagall = datafull(:, "tagId");
% Initialise x-coordinates
xall = datafull(:,"data__coordinates__x");
% Initialise y-ccordinates
yall = datafull(:, "data__coordinates__y");
```

```
%% Clean Data and Convert to Metres

% All coordinate data
coordsalltagsdirty = [timeall, tagall, xall, yall, uncertaintyall];
% Clean data
coordsalltagsclean = rmmissing(coordsalltagsdirty);
% Convert to m
coordsalltagsclean.data__coordinates__x = coordsalltagsclean.data__coordinates__x/1000;
coordsalltagsclean.data__coordinates__y = coordsalltagsclean.data__coordinates__y/1000;

%% Separate for User Inputs

% Separate for required tag
coordstag = coordsalltagsclean(ismember(coordsalltagsclean.tagId,inputtag,'rows'), :);
% Separate for required start and end time
range = coordstag.timestamp >= s & coordstag.timestamp <= e;
coordsrangeuncertain = coordstag(range, :);
% Align to start time at 0
coordsrangeuncertain.timestamp = coordsrangeuncertain.timestamp - s;
% Remove uncertainties according to threshold
uncertainty = coordsrangeuncertain.data__metrics__reliability__uncertainty <=
maxuncertainty;
coordsrange = coordsrangeuncertain(uncertainty, :);

%% Smooth and Filter Coordinate Data

finalcoords = smoothdata(coordsrange, 'movmedian', smoothcoords, 'DataVariables',
["data__coordinates__x", "data__coordinates__y"]);

%% Prepare for Coordinate Plots

% These measures assist in visualising the coordinate data to
% identify errors and ensure reliability prior to the calculation
% of other metrics including velocity.

% Define offset
xoff = -11.4;
yoff = -1;
theta = -3.28;

% Create platform boundary (12 m x 7.2)
boundpolyin = polyshape([0 0 12 12],[7.2 0 0 7.2]);
boundpoly1 = translate(boundpolyin, xoff, yoff);
boundpolyout = rotate(boundpoly1, theta); % Account for coordinate rotation

% Prepare coordinate plot for section separators
```

```
xsectionin = [1.2 1.2 10.8 10.8] + xoff;
ysection1in = [1.2 0 0 1.2] + yoff;
ysection2in = [4.8 1.2 1.2 4.8] + yoff;
ysection3in = [7.2 4.8 4.8 7.2] + yoff;

% Create section separators
section1polyin = polyshape(xsectionin, ysection1in);
section1polyout = rotate(section1polyin, theta);
section2polyin = polyshape(xsectionin, ysection2in);
section2polyout = rotate(section2polyin, theta);
section3polyin = polyshape(xsectionin, ysection3in);
section3polyout = rotate(section3polyin, theta);

% Prepare coordinate plot for walls
% Vertical walls
xwall0in = [1.15 1.15 1.25 1.25] + xoff;
ywall00in = [2.4 1.2 1.2 2.4] + yoff;
ywall01in = [4.8 3.6 3.6 4.8] + yoff;
wall00polyin = polyshape(xwall0in, ywall00in);
wall00polyout = rotate(wall00polyin, theta);
wall01polyin = polyshape(xwall0in, ywall01in);
wall01polyout = rotate(wall01polyin, theta);

xwall1in = [3.55 3.55 3.65 3.65] + xoff;
ywall10in = [3.6 1.2 1.2 3.6] + yoff;
wall10polyin = polyshape(xwall1in, ywall10in);
wall10polyout = rotate(wall10polyin, theta);

xwall2in = [5.95 5.95 6.05 6.05] + xoff;
ywall20in = [2.4 1.2 1.2 2.4] + yoff;
ywall21in = [4.8 3.6 3.6 4.8] + yoff;
wall20polyin = polyshape(xwall2in, ywall20in);
wall20polyout = rotate(wall20polyin, theta);
wall21polyin = polyshape(xwall2in, ywall21in);
wall21polyout = rotate(wall21polyin, theta);

xwall3in = [8.35 8.35 8.45 8.45] + xoff;
ywall30in = [4.8 2.4 2.4 4.8] + yoff;
wall30polyin = polyshape(xwall3in, ywall30in);
wall30polyout = rotate(wall30polyin, theta);

xwall4in = [9.55 9.55 9.65 9.65] + xoff;
ywall40in = [2.4 1.2 1.2 2.4] + yoff;
ywall41in = [4.8 3.6 3.6 4.8] + yoff;
wall40polyin = polyshape(xwall4in, ywall40in);
wall40polyout = rotate(wall40polyin, theta);
```

```
wall41polyin = polyshape(xwall4in, ywall41in);
wall41polyout = rotate(wall41polyin, theta);

xwall5in = [10.75 10.75 10.85 10.85] + xoff;
ywall50in = [2.4 1.2 1.2 2.4] + yoff;
ywall51in = [4.8 3.6 3.6 4.8] + yoff;
wall50polyin = polyshape(xwall5in, ywall50in);
wall50polyout = rotate(wall50polyin, theta);
wall51polyin = polyshape(xwall5in, ywall51in);
wall51polyout = rotate(wall51polyin, theta);

% Horizontal Walls
xwall6in = [1.2 1.2 10.8 10.8] + xoff;
ywall60in = [1.25 1.15 1.15 1.25] + yoff;
ywall61in = [4.85 4.75 4.75 4.85] + yoff;
wall60polyin = polyshape(xwall6in, ywall60in);
wall60polyout = rotate(wall60polyin, theta);
wall61polyin = polyshape(xwall6in, ywall61in);
wall61polyout = rotate(wall61polyin, theta);

%% Plot Coordinates

graphcoords = figure;
hold on
% Plot boundary
plot(boundpolyout, 'FaceColor', 'yellow', 'LineWidth', 3)
% Plot sections
plot(section1polyout, "LineStyle","--", 'LineWidth', 1)
plot(section2polyout, "LineStyle","--", 'LineWidth', 1)
plot(section3polyout, "LineStyle","--", 'LineWidth', 1)
% Plot walls
plot(wall00polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall01polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall10polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall20polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall21polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall30polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall40polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall41polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall50polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall51polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall60polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
plot(wall61polyout, 'FaceColor', 'k', 'FaceAlpha', 1)
% Plot coordinates
plot(finalcoords,"data__coordinates__x","data__coordinates__y", 'LineWidth', 1.5)
% Add plot title and axes titles
```

```
xlim([-12 2]) %-14 4
ylim([0 7]) % -2 8
axis equal
title(['Tag ',num2str(inputtag),' Coordinates'])
xlabel('x (m)')
ylabel('y (m)')
hold off
exportgraphics(graphcoords, 'Coords.png', 'Resolution', 700)

%% Calculate Velocity

% Create arrays of time and position
timestamparray = table2array(finalcoords(:, 'timestamp'));
xarray = table2array(finalcoords(:, 'data__coordinates__x'));
yarray = table2array(finalcoords(:, 'data__coordinates__y'));

% For loops to calculate displacement and velocity in x and y
xdisp = zeros(length(timestamparray)-1,1);
xvel = zeros(length(timestamparray)-1,1);
for i = 1:length(timestamparray)-1
    xdisp(i) = xarray(i+1)-xarray(i);
    timediff(i) = timestamparray(i+1)-timestamparray(i);
    xvel(i) = xdisp(i)/timediff(i);
end

ydisp = zeros(length(timestamparray)-1,1);
yvel = zeros(length(timestamparray)-1,1);
for i = 1:length(timestamparray)-1
    ydisp(i) = yarray(i+1)-yarray(i);
    yvel(i) = ydisp(i)/timediff(i);
end

% For loops to calculate scalar speed
speed = zeros(length(xvel),1);
for i = 1:length(xvel)
    speed(i) = sqrt(xvel(i)^2+yvel(i)^2);
end

% For loops to calculate scalar distance
distance = zeros(length(xvel),1);
for i = 1:length(xvel)
   distance(i) = sqrt(xdisp(i)^2+ydisp(i)^2);
end

% Compute and print total distance walked and path inefficiency
fprintf('For Tag %5.0f \n', inputtag);
```

```
totaldistance = sum(distance);
pathinefficiency = 100*(totaldistance-pathlength)/pathlength;
fprintf('Total Distance = %5.2f m and Path Length = %5.1f \n', totaldistance, pathlength);
fprintf('Path Inefficiency = %5.2f \n', pathinefficiency);
fprintf('\n');

% Compute and print average speed
speedtotal = totaldistance/(e-s);
meanspeed = mean(speed);
maxspeed = max(speed);
minspeed = min(speed);
fprintf('Duration = %5.0f s \n', duration);
fprintf('Total Avg Speed = %5.2f m/s \n', speedtotal);
fprintf('Mean Speed = %5.2f m/s \n', meanspeed);
fprintf('Max Speed = %5.2f m/s \n', maxspeed);
fprintf('Min Speed = %5.2f m/s \n', minspeed);

% Tabulate results
vels = table(timestamparray(2:end), xvel, yvel, speed, 'VariableNames', {'Time','Vel X','Vel Y',
'Speed'});

% Smooth and Filter Speed Data
finalvels = smoothdata(vels, 'movmedian', smoothspeed, 'DataVariables', ["Vel X","Vel
Y","Speed"]);

%% Plot Speed

graphspeed = figure;
hold on;
% Plot speed
plot(finalvels, 'Time', 'Speed', 'LineWidth', 1.5);
% Add plot title and axes titles
title(['Tag ',num2str(inputtag),' Speed']);
xlabel('Time (s)');
ylabel('Speed (m/s)');
hold off;
exportgraphics(graphspeed, 'Speed.png', 'Resolution', 700)

 %==================END OF PROGRAM==================
```

The means and standard deviations of the populations from which these two samples are extracted are denoted $\mu_A, \mu_A, \sigma_A, \sigma_B$ respectively. n_A and n_B represent the number in each sample.

The test statistic is defined as:

$$Z = \frac{(\bar{X}_A - \bar{X}_B) - (\mu_A - \mu_B)}{\sigma_{\bar{X}_A - \bar{X}_B}}$$

Where

$$\sigma_{\bar{X}_A - \bar{X}_B} = \sqrt{\frac{\sigma_A^2}{n_A} + \frac{\sigma_B^2}{n_B}}$$

is the standard deviation of the difference between the sample means.

Assuming a normal distribution

Null hypothesis H_0: $\mu_A = \mu_B$

Alternative hypothesis H_1: $\mu_A \neq \mu_B$

Level of significance: 0.05

The p value is attained from statistic tables.

Figure N1: Mean walking speed observed for different wayfinding systems (forward pass) (Wright et al., 1999)

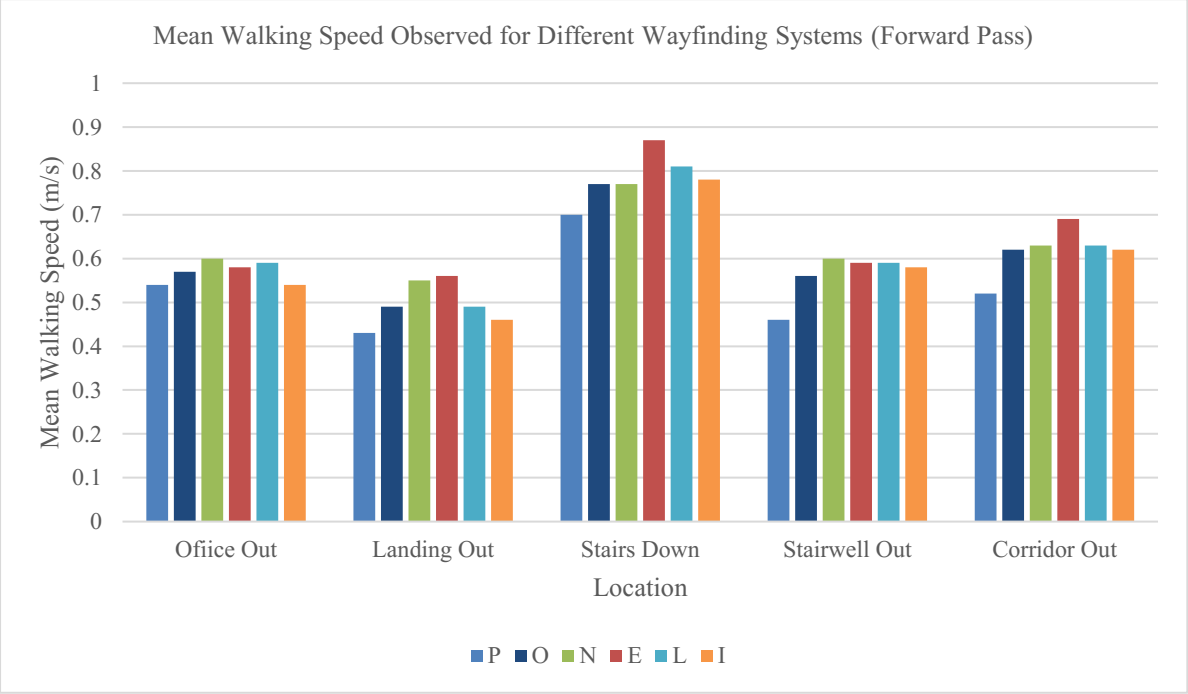


Figure N2: Mean walking speed observed for different wayfinding systems (return pass) (Wright et al., 1999)

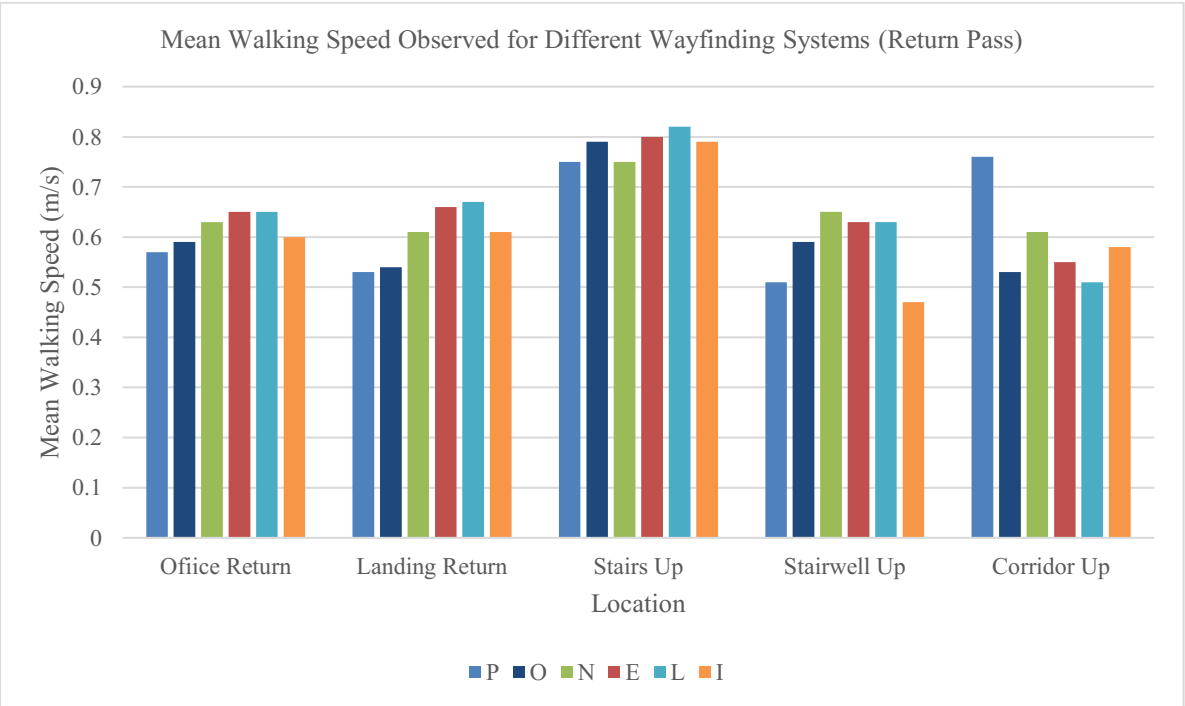


Figure N3: Inputs, outputs, and their prioritisation in the MoBIC system developed by Strothotte et al. (1996)

Command	Type	Parameter	Output
Where am I?	primary	-	position of user
Mute	primary	-	-
Alarm!	primary	-	confirmation
Repeat last message	primary	-	last message
Navigational instruction	primary	-	current instruction
Output level	primary	new level	confirmation
Tell me about orientation cues around me!	secondary	-	orientation cues
Where is the next "object"?	secondary	object	position of object, route leading to it
What is the estimated travel time to the destination?	secondary	object/ position	estimated travel time
Help on commands	secondary		help text

Appendix O – Supplementary Information for the Indoor Positioning System Developed by Alghananim et al. (2022)

Figure O1: Bluetooth and dead reckoning (EKF) positioning architecture

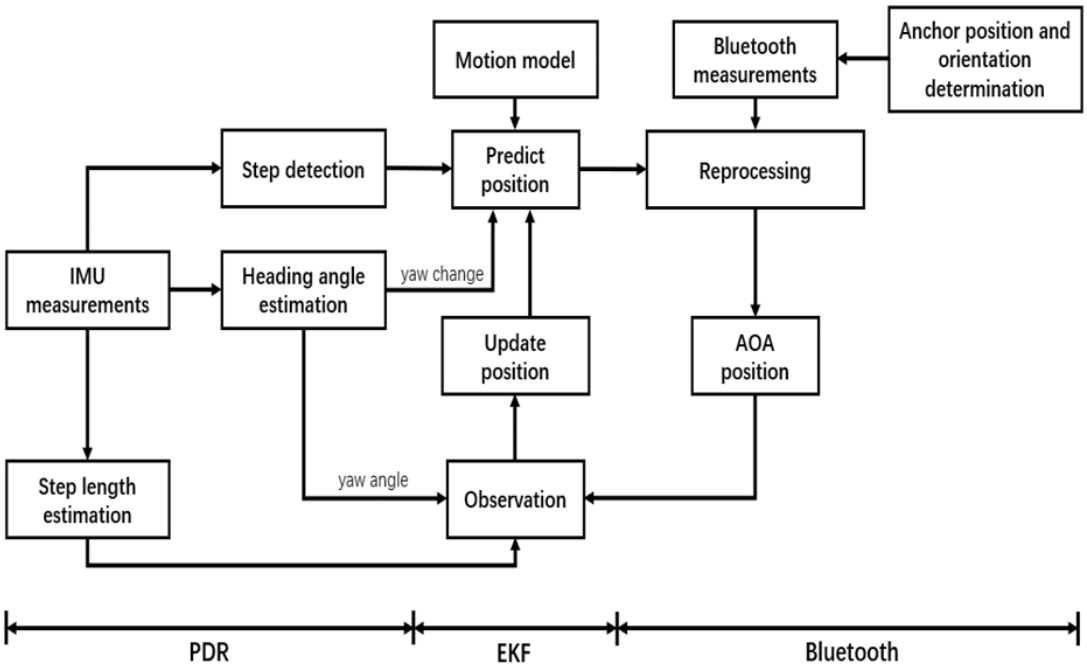
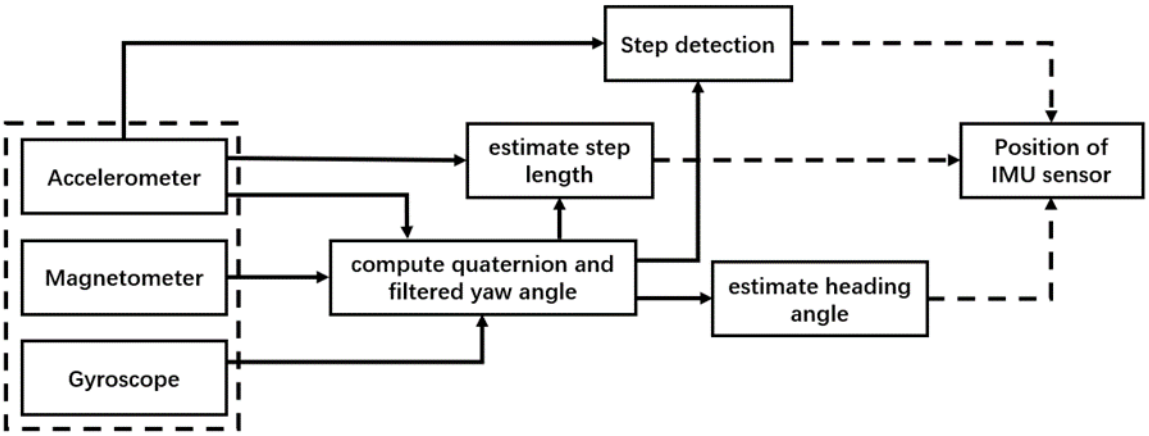


Figure O2: VIPDR architecture



Appendix P – VIP and NSP Walking Metrics from Indoor Positioning Experiment

Table P1: Times for VIPs and NSPs to traverse each section of the walking environment

ID	Time (s)																
	AB	**BC**	**CD**	**DA**	**AE**	**EB**	**BE**	**EC**	**CE**	**ED**	**DE**	**EA**	**AD**	**DC**	**CB**	**BA**	**Total**
V1	11.2	5.3	9.4	5.5	5.3	3.9	4.8	3.8	4.0	3.4	3.5	3.6	6.4	10.7	5.8	9.1	95.6
V2	11.9	6.0	10.0	5.6	3.3	5.6	4.4	3.8	4.6	3.7	4.3	7.1	7.9	11.6	7.5	10.1	107.3
V3	5.9	3.8	6.3	3.6	2.3	2.5	2.1	2.3	2.3	2.6	2.0	2.5	4.5	5.8	4.1	5.9	58.4
V4	6.5	4.2	5.6	4.0	2.5	2.6	2.7	2.8	3.0	2.8	2.4	2.7	4.3	5.7	3.7	5.3	60.8
V5 P1	9.9	6.7	9.1	6.7	4.9	5.3	4.4	5.6	4.7	4.1	4.0	4.0	6.5	8.4	6.0	9.6	99.9
V5 P2	8.9	6.5	9.6	6.8	4.7	4.8	4.7	4.5	5.0	4.0	3.4	3.6	6.5	9.2	6.5	9.8	98.5
V6	11.1	6.8	9.8	6.0	4.3	4.2	4.6	4.1	3.8	3.5	3.0	3.7	5.7	8.7	5.7	8.9	94.0
V7 P1	7.5	4.6	6.8	4.4	2.9	3.2	3.2	3.3	2.9	2.5	2.5	3.1	4.7	6.1	4.1	6.3	67.9
V7 P2	7.3	4.4	6.4	4.1	3.1	3.3	3.0	3.1	2.8	2.6	2.6	2.9	4.4	6.3	4.2	6.2	66.6
V8 P1	10.5	6.7	10.1	6.9	5.1	4.7	5.0	4.5	4.1	3.3	4.6	4.3	7.3	12.8	7.1	12.0	109.0
V8 P2	13.0	7.0	12.0	7.3	6.0	6.0	6.2	4.5	4.9	3.6	3.6	3.8	6.6	10.8	5.9	9.8	110.9
V9	11.9	7.3	10.4	6.9	4.4	5.1	4.7	5.0	5.2	4.4	4.5	5.3	6.8	10.3	6.8	9.5	108.2
V10	8.3	5.4	7.3	4.6	3.0	3.6	3.6	3.0	3.1	2.3	2.5	2.7	4.2	6.5	3.7	6.3	69.8
N1	7.3	4.6	7.3	5.0	3.4	3.5	3.3	3.4	3.2	2.8	3.3	3.2	5.1	7.4	4.9	7.6	75.3
N2	7.5	5.0	7.5	5.0	3.1	3.6	3.2	3.0	2.9	2.5	2.6	2.9	4.4	6.5	4.0	6.5	70.2
N3	7.9	5.0	7.7	5.2	3.2	4.0	3.6	3.6	3.3	2.8	2.9	3.6	5.2	7.2	4.6	7.6	77.3
N4	6.4	3.6	5.5	3.6	2.3	2.7	2.7	2.5	2.4	2.0	2.0	2.6	4.0	5.6	3.4	5.4	56.6
N5	6.6	4.3	5.7	3.8	2.8	2.6	3.0	2.8	2.9	2.5	2.3	2.9	3.8	5.4	3.6	5.1	60.1

Table P2: Average, standard deviation, and coefficient of variation of times for VIPs and NSPs to traverse each section of the walking environment (where a participant has completed several passes, only the first pass is considered in the calculation of these metrics)

ID	Time (s)																
	AB	**BC**	**CD**	**DA**	**AE**	**EB**	**BE**	**EC**	**CE**	**ED**	**DE**	**EA**	**AD**	**DC**	**CB**	**BA**	**Total**
VIP																	
Avg. VIP	9.4	5.7	8.5	5.4	3.8	4.1	3.9	3.8	3.8	3.2	3.3	3.9	5.8	8.7	5.5	8.3	87.1
SD VIP	2.3	1.2	1.8	1.2	1.1	1.1	1.0	1.0	0.9	0.7	1.0	1.4	1.4	2.6	1.4	2.2	20.5
CV VIP	23.9	21.1	21.1	22.5	29.8	26.9	24.7	26.6	24.6	21.4	29.3	36.3	23.3	30.2	26.6	26.8	23.6
NSP																	
Avg. N	7.1	4.5	6.7	4.5	3.0	3.3	3.2	3.1	2.9	2.5	2.6	3.0	4.5	6.4	4.1	6.4	67.9
SD N	0.6	0.6	1.1	0.8	0.4	0.6	0.3	0.4	0.3	0.3	0.5	0.4	0.6	0.9	0.6	1.2	9.2
CV N	9.0	12.9	15.6	16.7	15.1	18.7	10.7	14.7	11.3	12.8	19.4	12.1	14.2	14.2	15.6	18.2	13.5

Table P3: Effective speed of VIPs and NSPs traversing each section of the walking environment ('total' depicts the total path length divided by the total path time)

ID	Effective Speed (m/s)																
	AB	**BC**	**CD**	**DA**	**AE**	**EB**	**BE**	**EC**	**CE**	**ED**	**DE**	**EA**	**AD**	**DC**	**CB**	**BA**	**Total**
V1	0.7	0.9	0.8	0.9	0.6	1.0	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.7	0.9	0.9	0.8
V2	0.7	0.8	0.8	0.9	0.9	0.7	0.9	0.8	0.7	0.8	0.6	0.4	0.6	0.7	0.7	0.8	0.7
V3	1.4	1.3	1.3	1.4	1.4	1.6	1.9	1.4	1.4	1.0	1.4	1.2	1.1	1.4	1.2	1.4	1.3
V4	1.2	1.2	1.4	1.3	1.2	1.6	1.5	1.1	1.1	1.0	1.1	1.2	1.2	1.4	1.4	1.5	1.3
V5 P1	0.8	0.8	0.9	0.8	0.6	0.8	0.9	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.8	0.8	0.8
V5 P2	0.9	0.8	0.8	0.7	0.7	0.8	0.9	0.7	0.6	0.7	0.8	0.9	0.8	0.9	0.8	0.8	0.8
V6	0.7	0.7	0.8	0.8	0.7	0.9	0.9	0.8	0.8	0.8	0.9	0.8	0.9	0.9	0.9	0.9	0.8
V7 P1	1.1	1.1	1.2	1.1	1.1	1.2	1.3	1.0	1.1	1.1	1.1	1.0	1.1	1.3	1.2	1.3	1.2
V7 P2	1.1	1.2	1.3	1.2	1.0	1.2	1.3	1.0	1.1	1.1	1.1	1.1	1.1	1.3	1.2	1.3	1.2
V8 P1	0.8	0.8	0.8	0.7	0.6	0.9	0.8	0.7	0.8	0.8	0.6	0.7	0.7	0.6	0.7	0.7	0.7
V8 P2	0.6	0.7	0.7	0.7	0.5	0.7	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.7	0.9	0.8	0.7
V9	0.7	0.7	0.8	0.7	0.7	0.8	0.9	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.7	0.8	0.7
V10	1.0	0.9	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.1	1.2	1.2	1.2	1.4	1.3	1.1
N1	1.1	1.1	1.1	1.0	0.9	1.1	1.2	0.9	1.0	1.0	0.8	1.0	1.0	1.1	1.0	1.1	1.0
N2	1.1	1.0	1.1	1.0	1.0	1.1	1.3	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.3	1.2	1.1
N3	1.0	1.0	1.0	1.0	1.0	1.0	1.1	0.9	1.0	1.0	0.9	0.9	1.0	1.1	1.1	1.0	1.0
N4	1.3	1.4	1.4	1.4	1.4	1.5	1.5	1.3	1.3	1.4	1.4	1.2	1.3	1.4	1.5	1.5	1.4
N5	1.2	1.2	1.4	1.3	1.1	1.5	1.4	1.2	1.1	1.1	1.2	1.1	1.3	1.5	1.4	1.6	1.3

Table P4: Average, standard deviation, and coefficient of variation of effective speeds of VIPs and NSPs traversing each section of the walking environment (where a participant has completed several passes, only the first pass is considered in the calculation of these metrics)

ID	Effective Speed (m/s)																
	AB	**BC**	**CD**	**DA**	**AE**	**EB**	**BE**	**EC**	**CE**	**ED**	**DE**	**EA**	**AD**	**DC**	**CB**	**BA**	**Total**
VIP																	
Avg. VIP	0.9	0.9	1.0	1.0	0.9	1.1	1.1	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	0.9
SD VIP	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.2	0.3	0.3	0.3	0.2
CV VIP	27.7	23.2	23.8	24.2	31.5	30.0	32.1	27.5	27.1	22.0	30.4	29.9	23.8	30.1	27.6	28.3	26.0
NSP																	
Avg. N	1.1	1.1	1.2	1.1	1.1	1.2	1.3	1.1	1.1	1.1	1.1	1.0	1.1	1.3	1.3	1.3	1.2
SD N	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2
CV N	9.2	14.3	16.5	17.9	16.9	19.3	10.8	14.8	12.2	14.7	20.0	12.0	14.1	14.4	15.3	18.6	14.0

Appendix Q – Confidence Scores of VIPs and NSPs in Different Environments

Environment	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	N1	N2	N3	N4	N5	Avg. VIP	SD VIP	CV VIP	Avg. NSP	SD NSP	CV NSP
Bus terminal	3	1	4	3	2	3	3	1	2	2	5	4	3	3	4	2.4	1.0	40.3	3.8	0.8	22.0
Museum	1	3	3	3	2	1	4	1	2	4	5	5	3	4	4	2.4	1.2	48.9	4.2	0.8	19.9
Shared space	1	3	4	3	3	2	4	1	2	2	4	3	4	3	4	2.5	1.1	43.2	3.6	0.5	15.2
Through station	1	3	3	2	2	4	3	2	2	5	5	5	4	4	4	2.7	1.2	42.9	4.4	0.5	12.4
Taxi rank	3	3	3	4	3	2	3	1	2	4	4	4	3	3	5	2.8	0.9	32.8	3.8	0.8	22.0
Shopping centre	1	4	4	3	2	3	4	1	2	4	4	4	4	3	3	2.8	1.2	43.9	3.6	0.5	15.2
Theatre/Cinema	1	4	2	2	2	3	4	3	3	4	4	4	5	4	4	2.8	1.0	36.9	4.2	0.4	10.6
Bus stop	4	3	4	3	3	2	4	1	3	2	4	4	5	4	5	2.9	1.0	34.3	4.4	0.5	12.4
Airport	1	1	3	4	4	3	4	2	3	4	5	3	5	3	4	2.9	1.2	41.3	4.0	1.0	25.0
Stadium	1	4	3	3	4	3	4	1	2	4	4	4	3	2	3	2.9	1.2	41.3	3.2	0.8	26.1
Office/University building	1	3	5	4	4	2	4	1	2	3	5	4	5	4	5	2.9	1.4	47.3	4.6	0.5	11.9
Hospital	1	4	4	4	4	2	4	2	2	3	4	3	4	3	4	3.0	1.2	38.5	3.6	0.5	15.2
Public house	1	4	3	4	4	2	4	2	2	4	5	5	4	4	5	3.0	1.2	38.5	4.6	0.5	11.9
Gym	1	3	5	4	4	3	4	1	2	3	4	5	3	3	3	3.0	1.3	44.4	3.6	0.9	24.8
Outdoor	**1**	**4**	**4**	**4**	**4**	**3**	**4**	**2**	**2**	**3**	**5**	**5**	**5**	**5**	**5**	3.1	1.1	35.5	5.0	0.0	0.0
Street	1	4	5	4	4	2	4	2	2	3	5	4	5	4	5	3.1	1.3	41.5	4.6	0.5	11.9
Open space	1	2	4	5	3	3	3	3	4	3	5	5	4	5	4	3.1	1.1	35.5	4.6	0.5	11.9
Terminating station	1	4	5	4	2	3	4	2	3	3	5	5	5	4	4	3.1	1.2	38.6	4.6	0.5	11.9
Indoor	**1**	**5**	**4**	**4**	**3**	**3**	**3**	**3**	**3**	**3**	**5**	**5**	**3**	**5**	**5**	3.2	1.0	32.3	4.6	0.9	19.4
Restaurant/Eatery	1	4	4	3	3	3	4	2	3	5	5	5	5	4	5	3.2	1.1	35.5	4.8	0.4	9.3
Commercial unit	3	4	4	4	3	2	4	1	3	5	5	5	2	4	4	3.3	1.2	35.1	4.0	1.2	30.6
Local clinic	2	3	4	5	4	3	4	3	3	3	5	4	4	5	5	3.4	0.8	24.8	4.6	0.5	11.9
Sports hall	1	3	4	4	4	3	4	3	3	5	5	4	4	4	4	3.4	1.1	31.6	4.2	0.4	10.6
Hotel	1	4	4	4	4	4	4	3	2	4	5	5	5	4	4	3.4	1.1	31.6	4.6	0.5	11.9
Private dwelling	5	4	5	5	5	4	5	5	5	5	5	5	5	5	5	4.8	0.4	8.8	5.0	0.0	0.0
Avg.	1.6	3.4	3.9	3.7	3.3	2.7	3.8	2.0	2.6	3.6	4.7	4.4	4.1	3.8	4.3	**3.0**	**1.1**	**37.0**	**4.2**	**0.6**	**15.0**
SD	1.1	1.0	0.8	0.8	0.9	0.7	0.5	1.0	0.8	1.0	0.5	0.7	0.9	0.8	0.7	**0.5**	**0.2**	**8.1**	**0.5**	**0.3**	**7.4**
CV	71.9	28.3	20.1	21.8	27.2	27.1	12.3	52.0	30.0	26.6	10.2	16.1	22.3	20.8	15.8	**15.1**	**16.9**	**21.8**	**11.6**	**44.4**	**49.3**

Appendix R – Results from the Thematic Analysis of Challenges, Motivations, and Coping Mechanisms of Visually Impaired People in Different Environments

Environment	Theme	Frequency					
		CVL	PVL	B	VIP	NS	Total
Outdoor	Dependence on familiarity	3		3	**6**		**6**
	Obstacles - Positive						
	Obstacles - Negative	1		1	**2**	**1**	**3**
	Ground condition - Positive					**1**	**1**
	Ground condition - Negative			1	**1**		**1**
	Congestion - Positive						
	Congestion - Negative						
	Signage - Positive						
	Signage - Negative						
	Lighting - Positive		1		**1**		**1**
	Lighting - Negative					**1**	**1**
	Boundaries - Positive						
	Boundaries - Negative						
	Visual function - Positive		2		**2**	**1**	**3**
	Visual function - Negative			1	**1**	**1**	**2**
	Sighted assistance - Positive	1			**1**		**1**
	Sighted assistance - Negative						
	Technology - Positive	1			**1**	**1**	**2**
	Technology - Negative						
	Orientation - Positive			1	**1**	**2**	**3**
	Orientation - Negative			1	**1**		**1**
	Perception of independence and safety - Positive	1	2	1	**4**	**2**	**6**
	Perception of independence and safety - Negative			1	**1**		**1**
	Time - Positive			1	**1**		**1**
	Time - Negative						
	References to difficulty in certain spaces	1		2	**3**		**3**
	Infrequent use						
	Total	**8**	**5**	**13**	**26**	**10**	**36**
Indoor	Dependence on familiarity	2		2	**4**	**3**	**7**
	Obstacles - Positive			1	**1**		**1**
	Obstacles - Negative	2	1		**3**		**3**
	Ground condition - Positive					**1**	**1**
	Ground condition - Negative	2		1	**3**		**3**
	Congestion - Positive						
	Congestion - Negative						
	Signage - Positive					**1**	**1**
	Signage - Negative						
	Lighting - Positive						
	Lighting - Negative						
	Boundaries - Positive			1	**1**		**1**
	Boundaries - Negative						

	Visual function - Positive		1		**1**	**1**	**2**
	Visual function - Negative					**1**	**1**
	Sighted assistance - Positive	1		1	**2**	**1**	**3**
	Sighted assistance - Negative	2			**2**		**2**
	Technology - Positive						
	Technology - Negative						
	Orientation - Positive			1	**1**	**1**	**2**
	Orientation - Negative					**1**	**1**
	Perception of independence and safety - Positive		1	2	**3**	**1**	**4**
	Perception of independence and safety - Negative						
	Time - Positive						
	Time - Negative						
	References to difficulty in certain spaces		1	1	**2**		**2**
	Infrequent use						
	Total	**9**	**4**	**10**	**23**	**11**	**34**
Street	Dependence on familiarity	1		1	**2**	**1**	**3**
	Obstacles - Positive		1		**1**		**1**
	Obstacles - Negative	2	1	3	**6**	**1**	**7**
	Ground condition - Positive						
	Ground condition - Negative	2		1	**3**		**3**
	Congestion - Positive						
	Congestion - Negative	1		1	**2**	**2**	**4**
	Signage - Positive					**1**	**1**
	Signage - Negative						
	Lighting - Positive		1		**1**		**1**
	Lighting - Negative						
	Boundaries - Positive						
	Boundaries - Negative						
	Visual function - Positive					**1**	**1**
	Visual function - Negative		1		**1**		**1**
	Sighted assistance - Positive	1		2	**3**		**3**
	Sighted assistance - Negative						
	Technology - Positive	1			**1**	**2**	**3**
	Technology - Negative						
	Orientation - Positive	1			**1**	**2**	**3**
	Orientation - Negative			1	**1**		**1**
	Perception of independence and safety - Positive	2	1		**3**	**1**	**4**
	Perception of independence and safety - Negative	1		1	**2**		**2**
	Time - Positive	2			**2**		**2**
	Time - Negative					**1**	**1**
	References to difficulty in certain spaces	1			**1**	**1**	**2**
	Infrequent use						
	Total	**15**	**5**	**10**	**30**	**13**	**43**
Open space	Dependence on familiarity	1		1	**2**	**1**	**3**
	Obstacles - Positive	1			**1**		**1**
	Obstacles - Negative		1	1	**2**		**2**

	Ground condition - Positive			1	**1**		**1**
	Ground condition - Negative	2		1	**3**		**3**
	Congestion - Positive						
	Congestion - Negative						
	Signage - Positive						
	Signage - Negative						
	Lighting - Positive						
	Lighting - Negative		1		**1**	**1**	**2**
	Boundaries - Positive			1	**1**	**1**	**2**
	Boundaries - Negative	2	1	1	**4**		**4**
	Visual function - Positive						
	Visual function - Negative		2		**2**		**2**
	Sighted assistance - Positive	2			**2**		**2**
	Sighted assistance - Negative						
	Technology - Positive	1			**1**		**1**
	Technology - Negative						
	Orientation - Positive	1			**1**		**1**
	Orientation - Negative	1	2	1	**4**	**1**	**5**
	Perception of independence and safety - Positive	2			**2**	**2**	**4**
	Perception of independence and safety - Negative					**1**	**1**
	Time - Positive	2			**2**		**2**
	Time - Negative						
	References to difficulty or fear in certain spaces	1	1	1	**3**		**3**
	Infrequent use						
	Total	**16**	**8**	**8**	**32**	**7**	**39**
Shared space	Dependence on familiarity	1		1	**2**		**2**
	Obstacles - Positive						
	Obstacles - Negative	4	1	3	**8**	**4**	**12**
	Ground condition - Positive						
	Ground condition - Negative						
	Congestion - Positive		1		**1**		**1**
	Congestion - Negative	2		2	**4**	**3**	**7**
	Signage - Positive						
	Signage - Negative						
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative		1		**1**		**1**
	Auditory reference - Positive						
	Auditory reference - Negative			1	**1**		**1**
	Boundaries - Positive						
	Boundaries - Negative	4		1	**5**	**3**	**8**
	Visual function - Positive						
	Visual function - Negative						
	Sighted assistance - Positive	1	1		**2**		**2**
	Sighted assistance - Negative	1			**1**		**1**
	Technology - Positive						
	Technology - Negative						

	Orientation - Positive		1		**1**		**1**
	Orientation - Negative	2		2	**4**	**1**	**5**
	Perception of independence and safety - Positive		1		**1**		**1**
	Perception of independence and safety - Negative	3	1	2	**6**	**3**	**9**
	Time - Positive						
	Time - Negative					**1**	**1**
	References to difficulty or fear in certain spaces	3		2	**5**		**5**
	Infrequent use						
	Total	**21**	**7**	**14**	**42**	**15**	**57**
Bus stop	Dependence on familiarity	1		1	**2**	**1**	**3**
	Obstacles - Positive						
	Obstacles - Negative	1		1	**2**		**2**
	Ground condition - Positive						
	Ground condition - Negative						
	Congestion - Positive						
	Congestion - Negative	1		4	**5**	**1**	**6**
	Signage - Positive						
	Signage - Negative	1	2	1	**4**		**4**
	Lighting, colour, contrast - Positive		1		**1**		**1**
	Lighting, colour, contrast - Negative	1			**1**		**1**
	Auditory reference - Positive	1		1	**2**		**2**
	Auditory reference - Negative			2	**2**		**2**
	Boundaries - Positive						
	Boundaries - Negative						
	Visual function - Positive		1		**1**		**1**
	Visual function - Negative	2	2		**4**	**2**	**6**
	Sighted assistance - Positive	1		2	**3**		**3**
	Sighted assistance - Negative	2	1	2	**5**		**5**
	Technology - Positive	1			**1**	**2**	**3**
	Technology - Negative	2		1	**3**		**3**
	Orientation - Positive						
	Orientation - Negative			2	**2**	**1**	**3**
	Perception of independence and safety - Positive	1	1	1	**3**	**3**	**6**
	Perception of independence and safety - Negative	1	1	2	**4**		**4**
	Time - Positive						
	Time - Negative	2	1		**3**	**1**	**4**
	References to difficulty or fear in certain spaces	2	1	2	**5**	**1**	**6**
	Infrequent use						
	Total	**20**	**11**	**22**	**53**	**12**	**65**
Bus terminal	Dependence on familiarity	1	1		**2**	**1**	**3**
	Obstacles - Positive						
	Obstacles - Negative						
	Ground condition - Positive						
	Ground condition - Negative						
	Congestion - Positive	1			**1**		**1**
	Congestion - Negative			1	**1**	**2**	**3**

	Signage - Positive					**2**	**2**
	Signage - Negative	2	1		**3**	**1**	**4**
	Lighting, colour, contrast - Positive					**1**	**1**
	Lighting, colour, contrast - Negative		1		**1**		**1**
	Auditory reference - Positive						
	Auditory reference - Negative			1	**1**		**1**
	Boundaries - Positive					**1**	**1**
	Boundaries - Negative			3	**3**	**1**	**4**
	Visual function - Positive						
	Visual function - Negative	1	1		**2**		**2**
	Sighted assistance - Positive	3	1	3	**7**		**7**
	Sighted assistance - Negative			1	**1**		**1**
	Technology - Positive					**1**	**1**
	Technology - Negative	1			**1**		**1**
	Orientation - Positive					**1**	**1**
	Orientation - Negative	2	1	4	**7**	**1**	**8**
	Perception of independence and safety - Positive	1	1		**2**		**2**
	Perception of independence and safety - Negative	2	1	3	**6**		**6**
	Time - Positive						
	Time - Negative		1		**1**		**1**
	References to difficulty or fear in certain spaces		1	1	**2**	**1**	**3**
	Infrequent use	1	1		**2**	**1**	**3**
	Total	**15**	**11**	**17**	**43**	**14**	**57**
Taxi rank	Dependence on familiarity	1		1	**2**		**2**
	Obstacles - Positive						
	Obstacles - Negative	1		1	**2**	**1**	**3**
	Ground condition - Positive						
	Ground condition - Negative						
	Congestion - Positive	2			**2**		**2**
	Congestion - Negative	1			**1**	**1**	**2**
	Signage - Positive						
	Signage - Negative	1			**1**	**1**	**2**
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative	1			**1**	**1**	**2**
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive	1			**1**		**1**
	Boundaries - Negative						
	Visual function - Positive						
	Visual function - Negative	2	1		**3**		**3**
	Sighted assistance - Positive	1		2	**3**		**3**
	Sighted assistance - Negative	1		1	**2**	**1**	**3**
	Technology - Positive	1			**1**		**1**
	Technology - Negative						
	Orientation - Positive						
	Orientation - Negative	2		1	**3**		**3**

	Perception of independence and safety - Positive	1			**1**		**1**
	Perception of independence and safety - Negative	1		1	**2**	**1**	**3**
	Time - Positive						
	Time - Negative	1			**1**		**1**
	References to difficulty or fear in certain spaces	3	1	1	**5**	**1**	**6**
	Infrequent use		1		**1**	**3**	**4**
	Total	**21**	**3**	**8**	**32**	**10**	**42**
Through station	Dependence on familiarity	2		3	**5**	**1**	**6**
	Obstacles - Positive						
	Obstacles - Negative	2		2	**4**		**4**
	Ground condition - Positive						
	Ground condition - Negative			1	**1**		**1**
	Congestion - Positive	1			**1**	**1**	**2**
	Congestion - Negative	1		1	**2**	**2**	**4**
	Signage - Positive					**3**	**3**
	Signage - Negative	1	1		**2**	**1**	**3**
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative	1			**1**		**1**
	Auditory reference - Positive	1			**1**		**1**
	Auditory reference - Negative	1			**1**		**1**
	Boundaries - Positive						
	Boundaries - Negative	1		2	**3**		**3**
	Visual function - Positive					**1**	**1**
	Visual function - Negative	1			**1**		**1**
	Sighted assistance - Positive	2		3	**5**		**5**
	Sighted assistance - Negative		1		**1**		**1**
	Technology - Positive						
	Technology - Negative					**1**	**1**
	Orientation - Positive	1			**1**		**1**
	Orientation - Negative	3	2	4	**9**	**1**	**10**
	Perception of independence and safety - Positive	2	1	1	**4**		**4**
	Perception of independence and safety - Negative	1		2	**3**		**3**
	Time - Positive						
	Time - Negative	1	1		**2**	**1**	**3**
	References to difficulty or fear in certain spaces	4	2	3	**9**	**1**	**10**
	Infrequent use						
	Total	**26**	**8**	**22**	**56**	**13**	**69**
Terminating station	Dependence on familiarity	1		4	**5**	**1**	**6**
	Obstacles - Positive						
	Obstacles - Negative						
	Ground condition - Positive						
	Ground condition - Negative						
	Congestion - Positive	1	1		**2**	**1**	**3**
	Congestion - Negative	1			**1**	**1**	**2**
	Signage - Positive		2		**2**	**1**	**3**
	Signage - Negative	1			**1**	**1**	**2**

	Lighting, colour, contrast - Positive		1		**1**		**1**
	Lighting, colour, contrast - Negative						
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive						
	Boundaries - Negative	2			**2**		**2**
	Visual function - Positive						
	Visual function - Negative						
	Sighted assistance - Positive	1		3	**4**		**4**
	Sighted assistance - Negative			1	**1**		**1**
	Technology - Positive						
	Technology - Negative						
	Orientation - Positive	2	1	1	**4**		**4**
	Orientation - Negative	2	1	1	**4**		**4**
	Perception of independence and safety - Positive	2	1	1	**4**	**2**	**6**
	Perception of independence and safety - Negative			1	**1**		**1**
	Time - Positive						
	Time - Negative						
	References to difficulty or fear in certain spaces	2		2	**4**	**1**	**5**
	Infrequent use						
	Total	**15**	**7**	**14**	**36**	**8**	**44**
Airport	Dependence on familiarity					**2**	**2**
	Obstacles - Positive			1	**1**		**1**
	Obstacles - Negative						
	Ground condition - Positive						
	Ground condition - Negative						
	Congestion - Positive	1			**1**		**1**
	Congestion - Negative			2	**2**	**2**	**4**
	Signage - Positive		2		**2**	**2**	**4**
	Signage - Negative	1			**1**	**1**	**2**
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative	1			**1**		**1**
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive					**1**	**1**
	Boundaries - Negative			2	**2**	**1**	**3**
	Visual function - Positive		1		**1**		**1**
	Visual function - Negative	1			**1**	**1**	**2**
	Sighted assistance - Positive	4		4	**8**		**8**
	Sighted assistance - Negative	3		1	**4**		**4**
	Technology - Positive	1			**1**		**1**
	Technology - Negative						
	Orientation - Positive			2	**2**		**2**
	Orientation - Negative	3	1	3	**7**	**2**	**9**
	Perception of independence and safety - Positive	2	2		**4**	**2**	**6**
	Perception of independence and safety - Negative			2	**2**	**1**	**3**

	Time - Positive	2		1	**3**		**3**
	Time - Negative					**2**	**2**
	References to difficulty or fear in certain spaces	2		3	**5**	**2**	**7**
	Infrequent use						
	Total	**21**	**6**	**21**	**48**	**19**	**67**
Shopping centre	Dependence on familiarity	1			**1**		**1**
	Obstacles - Positive						
	Obstacles - Negative	1	1	1	**3**		**3**
	Ground condition - Positive						
	Ground condition - Negative						
	Congestion - Positive	1			**1**		**1**
	Congestion - Negative	1	1		**2**		**2**
	Signage - Positive						
	Signage - Negative	2			**2**	**1**	**3**
	Lighting, colour, contrast - Positive	1			**1**		**1**
	Lighting, colour, contrast - Negative	1			**1**		**1**
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive	1			**1**		**1**
	Boundaries - Negative			1	**1**	**1**	**2**
	Visual function - Positive						
	Visual function - Negative	2			**2**		**2**
	Sighted assistance - Positive	2		3	**5**		**5**
	Sighted assistance - Negative						
	Technology - Positive						
	Technology - Negative	1			**1**	**2**	**3**
	Orientation - Positive		1	1	**2**		**2**
	Orientation - Negative	1	1	3	**5**	**5**	**10**
	Perception of independence and safety - Positive	1		1	**2**		**2**
	Perception of independence and safety - Negative	2	1		**3**	**3**	**6**
	Time - Positive	1			**1**	**1**	**2**
	Time - Negative						
	References to difficulty or fear in certain spaces	3		2	**5**	**2**	**7**
	Infrequent use						
	Total	**22**	**5**	**12**	**39**	**15**	**54**
Commercial unit	Dependence on familiarity	1		3	**4**	**2**	**6**
	Obstacles - Positive						
	Obstacles - Negative						
	Ground condition - Positive						
	Ground condition - Negative						
	Congestion - Positive						
	Congestion - Negative						
	Signage - Positive						
	Signage - Negative	2	1		**3**	**1**	**4**
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative						

	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive	1	1	2	**4**	**1**	**5**
	Boundaries - Negative						
	Visual function - Positive						
	Visual function - Negative	1			**1**		**1**
	Sighted assistance - Positive	2		4	**6**		**6**
	Sighted assistance - Negative	1			**1**		**1**
	Technology - Positive	1			**1**		**1**
	Technology - Negative						
	Orientation - Positive	1		2	**3**		**3**
	Orientation - Negative		1		**1**	**2**	**3**
	Perception of independence and safety - Positive	1		2	**3**	**3**	**6**
	Perception of independence and safety - Negative		1	1	**2**	**1**	**3**
	Time - Positive	1			**1**		**1**
	Time - Negative					**1**	**1**
	References to difficulty or fear in certain spaces	4	1	3	**8**	**2**	**10**
	Infrequent use						
	Total	**16**	**5**	**17**	**38**	**13**	**51**
Restaurant/Eatery	Dependence on familiarity			1	**1**		**1**
	Obstacles - Positive						
	Obstacles - Negative		1	1	**2**	**1**	**3**
	Ground condition - Positive						
	Ground condition - Negative	1			**1**		**1**
	Congestion - Positive						
	Congestion - Negative	1		1	**2**	**1**	**3**
	Signage - Positive						
	Signage - Negative	2	1		**3**		**3**
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative	1			**1**		**1**
	Auditory reference - Positive			1	**1**		**1**
	Auditory reference - Negative						
	Boundaries - Positive					**1**	**1**
	Boundaries - Negative	1			**1**	**1**	**2**
	Visual function - Positive						
	Visual function - Negative		1		**1**		**1**
	Sighted assistance - Positive	4	1	2	**7**	**2**	**9**
	Sighted assistance - Negative	2		1	**3**		**3**
	Technology - Positive	1			**1**		**1**
	Technology - Negative			1	**1**		**1**
	Orientation - Positive	1			**1**	**1**	**2**
	Orientation - Negative	1	1	2	**4**		**4**
	Perception of independence and safety - Positive	2	2	1	**5**	**2**	**7**
	Perception of independence and safety - Negative			1	**1**		**1**
	Time - Positive						
	Time - Negative						

	References to difficulty or fear in certain spaces	3	1	2	**6**		**6**
	Infrequent use					**1**	**1**
	Total	**20**	**8**	**14**	**42**	**10**	**52**
Hospital	Dependence on familiarity	1		2	**3**		**3**
	Obstacles - Positive		1		**1**		**1**
	Obstacles - Negative		1		**1**		**1**
	Ground condition - Positive						
	Ground condition - Negative						
	Congestion - Positive	1			**1**	**1**	**2**
	Congestion - Negative						
	Signage - Positive					**1**	**1**
	Signage - Negative	2	1	1	**4**	**2**	**6**
	Lighting, colour, contrast - Positive		1		**1**		**1**
	Lighting, colour, contrast - Negative	1			**1**		**1**
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive						
	Boundaries - Negative	2		1	**3**	**1**	**4**
	Visual function - Positive						
	Visual function - Negative	1			**1**		**1**
	Sighted assistance - Positive	1		2	**3**	**1**	**4**
	Sighted assistance - Negative	3	1		**4**	**1**	**5**
	Technology - Positive	1			**1**		**1**
	Technology - Negative						
	Orientation - Positive						
	Orientation - Negative	3	1	2	**6**	**4**	**10**
	Perception of independence and safety - Positive	1		2	**3**	**1**	**4**
	Perception of independence and safety - Negative	3		1	**4**		**4**
	Time - Positive						
	Time - Negative	1		1	**2**	**1**	**3**
	References to difficulty or fear in certain spaces	2	1	3	**6**	**2**	**8**
	Infrequent use					**1**	**1**
	Total	**23**	**7**	**15**	**45**	**16**	**61**
Local clinic	Dependence on familiarity	2		1	**3**		**3**
	Obstacles - Positive						
	Obstacles - Negative	1		1	**2**		**2**
	Ground condition - Positive						
	Ground condition - Negative			1	**1**		**1**
	Congestion - Positive	1			**1**		**1**
	Congestion - Negative			1	**1**		**1**
	Signage - Positive						
	Signage - Negative					**1**	**1**
	Lighting, colour, contrast - Positive		1		**1**		**1**
	Lighting, colour, contrast - Negative						
	Auditory reference - Positive						
	Auditory reference - Negative			1	**1**		**1**

	Boundaries - Positive	1	1	2	**4**	**4**	**8**
	Boundaries - Negative			1	**1**		**1**
	Visual function - Positive						
	Visual function - Negative						
	Sighted assistance - Positive	2	1	2	**5**	**2**	**7**
	Sighted assistance - Negative			1	**1**		**1**
	Technology - Positive						
	Technology - Negative						
	Orientation - Positive	1	1	2	**4**		**4**
	Orientation - Negative	1			**1**		**1**
	Perception of independence and safety - Positive	1	1	3	**5**	**2**	**7**
	Perception of independence and safety - Negative	1			**1**		**1**
	Time - Positive						
	Time - Negative	1			**1**		**1**
	References to difficulty or fear in certain spaces	2		2	**4**		**4**
	Infrequent use	1			**1**		**1**
	Total	**15**	**5**	**18**	**38**	**9**	**47**
Public house	Dependence on familiarity	1	1		**2**	**1**	**3**
	Obstacles - Positive						
	Obstacles - Negative	2	2		**4**		**4**
	Ground condition - Positive						
	Ground condition - Negative	1		1	**2**		**2**
	Congestion - Positive			1	**1**		**1**
	Congestion - Negative	2	1		**3**	**2**	**5**
	Signage - Positive	1			**1**		**1**
	Signage - Negative						
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative	3	2		**5**		**5**
	Auditory reference - Positive						
	Auditory reference - Negative	1			**1**		**1**
	Boundaries - Positive					**1**	**1**
	Boundaries - Negative		1		**1**		**1**
	Visual function - Positive						
	Visual function - Negative						
	Sighted assistance - Positive	2	1	2	**5**	**1**	**6**
	Sighted assistance - Negative						
	Technology - Positive			1	**1**		**1**
	Technology - Negative						
	Orientation - Positive						
	Orientation - Negative	1	1	2	**4**	**1**	**5**
	Perception of independence and safety - Positive	2	1	2	**5**	**1**	**6**
	Perception of independence and safety - Negative			1	**1**	**1**	**2**
	Time - Positive	1			**1**		**1**
	Time - Negative						
	References to difficulty or fear in certain spaces	2	2	2	**6**	**1**	**7**
	Infrequent use						

	Total	**19**	**12**	**12**	**43**	**9**	**52**
Museum	Dependence on familiarity		1		**1**	**1**	**2**
	Obstacles - Positive						
	Obstacles - Negative	1		1	**2**		**2**
	Ground condition - Positive	1			**1**		**1**
	Ground condition - Negative						
	Congestion - Positive					**1**	**1**
	Congestion - Negative	1			**1**	**1**	**2**
	Signage - Positive					**1**	**1**
	Signage - Negative	2	1		**3**		**3**
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative	1			**1**		**1**
	Auditory reference - Positive	1	1	1	**3**		**3**
	Auditory reference - Negative	1		1	**2**		**2**
	Boundaries - Positive					**2**	**2**
	Boundaries - Negative	1		3	**4**	**1**	**5**
	Visual function - Positive						
	Visual function - Negative		1	1	**2**		**2**
	Sighted assistance - Positive	3		2	**5**		**5**
	Sighted assistance - Negative						
	Technology - Positive	1		1	**2**		**2**
	Technology - Negative	2			**2**		**2**
	Orientation - Positive					**3**	**3**
	Orientation - Negative	2	1	2	**5**	**1**	**6**
	Perception of independence and safety - Positive	1		1	**2**	**2**	**4**
	Perception of independence and safety - Negative	1	1	3	**5**		**5**
	Time - Positive					**1**	**1**
	Time - Negative					**1**	**1**
	References to difficulty or fear in certain spaces	2	1	1	**4**	**2**	**6**
	Infrequent use						
	Total	**21**	**7**	**17**	**45**	**17**	**62**
Theatre/Cinema	Dependence on familiarity	1			**1**	**2**	**3**
	Obstacles - Positive						
	Obstacles - Negative					**1**	**1**
	Ground condition - Positive						
	Ground condition - Negative	1			**1**		**1**
	Congestion - Positive	2			**2**		**2**
	Congestion - Negative					**2**	**2**
	Signage - Positive						
	Signage - Negative	2	2		**4**		**4**
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative	1	2		**3**	**1**	**4**
	Auditory reference - Positive						
	Auditory reference - Negative			1	**1**		**1**
	Boundaries - Positive			1	**1**		**1**
	Boundaries - Negative			1	**1**	**1**	**2**

	Visual function - Positive						
	Visual function - Negative	1	2		**3**		**3**
	Sighted assistance - Positive	4		2	**6**		**6**
	Sighted assistance - Negative	1			**1**		**1**
	Technology - Positive	1	1		**2**	**1**	**3**
	Technology - Negative			1	**1**		**1**
	Orientation - Positive			1	**1**	**1**	**2**
	Orientation - Negative	2	2	1	**5**	**1**	**6**
	Perception of independence and safety - Positive	1		2	**3**	**1**	**4**
	Perception of independence and safety - Negative	2			**2**	**1**	**3**
	Time - Positive			1	**1**	**1**	**2**
	Time - Negative	2	1		**3**		**3**
	References to difficulty or fear in certain spaces	2	2	2	**6**		**6**
	Infrequent use					**1**	**1**
	Total	**23**	**12**	**13**	**48**	**14**	**62**
Stadium	Dependence on familiarity						
	Obstacles - Positive						
	Obstacles - Negative	1			**1**	**1**	**2**
	Ground condition - Positive						
	Ground condition - Negative	1			**1**		**1**
	Congestion - Positive	2			**2**		**2**
	Congestion - Negative			3	**3**	**4**	**7**
	Signage - Positive	1			**1**		**1**
	Signage - Negative		1		**1**		**1**
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative	1			**1**		**1**
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive					**1**	**1**
	Boundaries - Negative			1	**1**	**1**	**2**
	Visual function - Positive	1			**1**		**1**
	Visual function - Negative			1	**1**		**1**
	Sighted assistance - Positive	4	1	4	**9**	**1**	**10**
	Sighted assistance - Negative						
	Technology - Positive	1			**1**		**1**
	Technology - Negative						
	Orientation - Positive						
	Orientation - Negative		2	1	**3**	**2**	**5**
	Perception of independence and safety - Positive	1		1	**2**		**2**
	Perception of independence and safety - Negative	3		4	**7**	**2**	**9**
	Time - Positive						
	Time - Negative			1	**1**		**1**
	References to difficulty or fear in certain spaces			1	**1**	**2**	**3**
	Infrequent use	2	1	1	**4**	**2**	**6**
	Total	**18**	**5**	**18**	**41**	**16**	**57**
	Dependence on familiarity	2	1		**3**	**3**	**6**

Office/University building	Obstacles - Positive		1		**1**		**1**
	Obstacles - Negative	3		1	**4**		**4**
	Ground condition - Positive	1			**1**		**1**
	Ground condition - Negative			1	**1**		**1**
	Congestion - Positive						
	Congestion - Negative	1			**1**		**1**
	Signage - Positive					**1**	**1**
	Signage - Negative	1	1		**2**	**2**	**4**
	Lighting, colour, contrast - Positive		1		**1**		**1**
	Lighting, colour, contrast - Negative			1	**1**		**1**
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive		1		**1**	**2**	**3**
	Boundaries - Negative	1			**1**		**1**
	Visual function - Positive		1		**1**		**1**
	Visual function - Negative	1			**1**		**1**
	Sighted assistance - Positive	1		3	**4**	**3**	**7**
	Sighted assistance - Negative	2			**2**	**1**	**3**
	Technology - Positive						
	Technology - Negative						
	Orientation - Positive	1	1		**2**	**3**	**5**
	Orientation - Negative	2		1	**3**	**1**	**4**
	Perception of independence and safety - Positive	2	2		**4**	**3**	**7**
	Perception of independence and safety - Negative	1		2	**3**		**3**
	Time - Positive	1			**1**		**1**
	Time - Negative						
	References to difficulty or fear in certain spaces	4		2	**6**	**1**	**7**
	Infrequent use						
	Total	**24**	**9**	**11**	**44**	**20**	**64**
Private dwelling	Dependence on familiarity	4	2	3	**9**	**5**	**14**
	Obstacles - Positive	1			**1**		**1**
	Obstacles - Negative	1		1	**2**	**1**	**3**
	Ground condition - Positive	1			**1**		**1**
	Ground condition - Negative						
	Congestion - Positive						
	Congestion - Negative						
	Signage - Positive						
	Signage - Negative						
	Lighting, colour, contrast - Positive		1		**1**		**1**
	Lighting, colour, contrast - Negative						
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive	1		1	**2**		**2**
	Boundaries - Negative			1	**1**		**1**
	Visual function - Positive						
	Visual function - Negative						

	Sighted assistance - Positive	1		1	**2**		**2**
	Sighted assistance - Negative						
	Technology - Positive						
	Technology - Negative						
	Orientation - Positive	3	2	2	**7**	**2**	**9**
	Orientation - Negative	1			**1**		**1**
	Perception of independence and safety - Positive	4	2	4	**10**	**5**	**15**
	Perception of independence and safety - Negative						
	Time - Positive						
	Time - Negative						
	References to difficulty or fear in certain spaces	2			**2**		**2**
	Infrequent use						
	Total	**19**	**7**	**13**	**39**	**13**	**52**
Gym	Dependence on familiarity	1	1	1	**3**		**3**
	Obstacles - Positive		1	1	**2**		**2**
	Obstacles - Negative	3	1	1	**5**		**5**
	Ground condition - Positive						
	Ground condition - Negative	2		1	**3**		**3**
	Congestion - Positive						
	Congestion - Negative	2		1	**3**	**2**	**5**
	Signage - Positive						
	Signage - Negative	1			**1**		**1**
	Lighting, colour, contrast - Positive						
	Lighting, colour, contrast - Negative						
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive		1		**1**	**1**	**2**
	Boundaries - Negative					**1**	**1**
	Visual function - Positive						
	Visual function - Negative						
	Sighted assistance - Positive	2		3	**5**		**5**
	Sighted assistance - Negative	1			**1**		**1**
	Technology - Positive						
	Technology - Negative	2			**2**	**3**	**5**
	Orientation - Positive		1		**1**		**1**
	Orientation - Negative		1	1	**2**	**2**	**4**
	Perception of independence and safety - Positive			1	**1**	**1**	**2**
	Perception of independence and safety - Negative	2		2	**4**	**1**	**5**
	Time - Positive						
	Time - Negative	1			**1**	**1**	**2**
	References to difficulty or fear in certain spaces	2	1	2	**5**	**1**	**6**
	Infrequent use	2	1	2	**5**	**1**	**6**
	Total	**21**	**8**	**16**	**45**	**14**	**59**
Sports hall	Dependence on familiarity	1		2	**3**	**1**	**4**
	Obstacles - Positive	1		1	**2**		**2**
	Obstacles - Negative	2			**2**		**2**

	Ground condition - Positive	1			**1**		**1**
	Ground condition - Negative	1			**1**		**1**
	Congestion - Positive					**1**	**1**
	Congestion - Negative	1			**1**		**1**
	Signage - Positive						
	Signage - Negative						
	Lighting, colour, contrast - Positive	1			**1**		**1**
	Lighting, colour, contrast - Negative	1	2		**3**		**3**
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive			1	**1**	**2**	**3**
	Boundaries - Negative	1	1	1	**3**	**1**	**4**
	Visual function - Positive						
	Visual function - Negative		2		**2**		**2**
	Sighted assistance - Positive	2		1	**3**		**3**
	Sighted assistance - Negative						
	Technology - Positive						
	Technology - Negative						
	Orientation - Positive					**2**	**2**
	Orientation - Negative			1	**1**	**2**	**3**
	Perception of independence and safety - Positive	3	1	2	**6**	**1**	**7**
	Perception of independence and safety - Negative			1	**1**		**1**
	Time - Positive						
	Time - Negative		1		**1**		**1**
	References to difficulty or fear in certain spaces	2	2	1	**5**	**2**	**7**
	Infrequent use	1		2	**3**		**3**
	Total	**18**	**9**	**13**	**40**	**12**	**52**
Hotel	Dependence on familiarity	3	2	3	**8**		**8**
	Obstacles - Positive						
	Obstacles - Negative						
	Ground condition - Positive						
	Ground condition - Negative	1			**1**		**1**
	Congestion - Positive						
	Congestion - Negative						
	Signage - Positive	1			**1**	**2**	**3**
	Signage - Negative	1	1		**2**		**2**
	Lighting, colour, contrast - Positive	1			**1**		**1**
	Lighting, colour, contrast - Negative		1		**1**		**1**
	Auditory reference - Positive						
	Auditory reference - Negative						
	Boundaries - Positive	2		2	**4**	**1**	**5**
	Boundaries - Negative					**1**	**1**
	Visual function - Positive	1			**1**		**1**
	Visual function - Negative	1			**1**		**1**
	Sighted assistance - Positive	2		3	**5**	**2**	**7**
	Sighted assistance - Negative	1			**1**		**1**

	Technology - Positive	1			**1**		**1**
	Technology - Negative	2			**2**		**2**
	Orientation - Positive	3		2	**5**	**3**	**8**
	Orientation - Negative		2		**2**	**2**	**4**
	Perception of independence and safety - Positive	3		3	**6**	**2**	**8**
	Perception of independence and safety - Negative						
	Time - Positive			1	**1**		**1**
	Time - Negative						
	References to difficulty or fear in certain spaces	2	1		**3**	**1**	**4**
	Infrequent use						
	Total	**25**	**7**	**14**	**46**	**14**	**60**