Perception and Orientation in Minimally Invasive Surgery

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This thesis is submitted to Imperial College of Science, Technology and Medicine in partial fulfilment of the requirements for the degree of Doctor of Philosophy. Except for where indicated, it presents entirely my own work and describes the results of my own research.

ABSTRACT

During the last two decades, we have seen a revolution in the way that we perform abdominal surgery with increased reliance on minimally invasive techniques. This paradigm shift has come at a rapid pace, with laparoscopic surgery now representing the gold standard for many surgical procedures and further minimisation of invasiveness being seen with the recent clinical introduction of novel techniques such as single-incision laparoscopic surgery and natural orifice translumenal endoscopic surgery. Despite the obvious benefits conferred on the patient in terms of morbidity, length of hospital stay and post-operative pain, this paradigm shift comes at a significantly higher demand on the surgeon, in terms of both perception and manual dexterity. The issues involved include degradation of sensory input to the operator compared to conventional open surgery owing to a loss of three-dimensional vision through the use of the two-dimensional operative interface, and decreased haptic feedback from the instruments. These changes have led to a much higher cognitive load on the surgeon and a greater risk of operator disorientation leading to potential surgical errors.

This thesis represents a detailed investigation of disorientation in minimally invasive surgery. In this thesis, eye tracking methodology is identified as the method of choice for evaluating behavioural patterns during orientation. An analysis framework is proposed to profile orientation behaviour using eye tracking data validated in a laboratory model. This framework is used to characterise and quantify successful orientation strategies at critical stages of laparoscopic cholecystectomy and furthermore use these strategies to prove that focused teaching of this behaviour in novices can significantly increase performance in this task. Orientation strategies are then characterised for common clinical scenarios in natural orifice translumenal endoscopic surgery and the concept of image saliency is introduced to further investigate the importance of specific visual cues associated with effective orientation. Profiling of behavioural patterns is related to performance in orientation and implications on education and construction of smart surgical robots are drawn. Finally, a method for potentially decreasing operator disorientation is

investigated in the form of endoscopic horizon stabilization in a simulated operative model for transgastric surgery.

The major original contributions of this thesis include:

- Validation of a profiling methodology/framework to characterise orientation behaviour
- Identification of high performance orientation strategies in specific clinical scenarios including laparoscopic cholecystectomy and natural orifice translumenal endoscopic surgery
- Evaluation of the efficacy of teaching orientation strategies
- Evaluation of automatic endoscopic horizon stabilization in natural orifice translumenal endoscopic surgery

The impact of the results presented in this thesis, as well as the potential for further high impact research is discussed in the context of both eye tracking as an evaluation tool in minimally invasive surgery as well as implementation of means to combat operator disorientation in a surgical platform. The work also provides further insight into the practical implementation of computer-assistance and technological innovation in future flexible access surgical platforms.

ACKNOWLEDGEMENTS

"There are things known and there are things unknown, and in between are the doors of perception"

James Douglas Morrison, The Doors 1943-1971

This quote by Jim Morrison was used to describe how the name of The Doors was conceived as one of the most successful and influential rock bands of the 20th century. He had taken his inspiration from the American philosopher Aldous Huxley (1894-1963) who famously wrote the book entitled 'The Doors of Perception' which was in turn based on ideas from the poet and painter William Blake (1757-1827). Although the difference in context could not be starker, it is befitting as an introductory quote as this thesis has similarly aimed to open one of the doors perception.

First and foremost I would like to thank my supervisors *Dr Julian Teare, Professor Guang-Zhong Yang* and *Professor Lord Ara Darzi*. Their encouragement and support has made this PhD one of the most motivating and rewarding experiences of my life. Their infinite appetite for innovation and scientific excellence is truly inspirational and has undoubtedly shaped the future of my professional career. I am particularly grateful to them for allowing me to guide the direction of this research and for providing the structure and support to cultivate and develop my ideas.

I have been privileged to work with some outstanding clinicians and scientists who have all in some way contributed to this thesis. I would like to thank my fellow clinicians working jointly in the Department of Biosurgery and Surgical Technology and Hamlyn Centre for Robotics Surgery at Imperial College London: *James Clark, David James, Richard Newton, Vahe Karimyan, Daniel Leff and Aimee DiMarco*. I would also like to thank the scientists and engineers at the Hamlyn Centre for Robotic Surgery, Imperial College: *David Noonan, George Mylonas, Jiangzhong Shang, Alexander Warren, Christopher Payne, Peter Mountney, Dan Elson and Danail Stoyanov*. I have been very grateful to work with some excellent clinician scientists in the Department of Biosurgery and Surgical Technology and St.Mary's Hospital, Imperial College who deserve my thanks: *Sanjay Purkayastha, Barry Paraskeva, Thanos Athanasiou, Andre Chow, Chris Nicolay, Ravi Mamidanna, Shantanu Rout, Colin Sugden, Vishal Patel, Sonal Arora, Hutan Ashrafian, James Kinross, Rajesh Aggarwal and Elaine Burns*. I would also like to thank all the kind scientists, engineers and clinicians who have given up their time and participated in the experiments of this thesis.

I would like to extend special thanks to *Dr Felipe Orihuela-Espina*, who has not only been an immense help in data analysis but his support and dedication to his work is beyond doubt exceptional. I am indebted to him for sharing with me his values of scientific rigour and for teaching me the inquisitive, methodical and meticulous problem-solving attributes and attitudes necessary to become a successful scientist.

Finally I would like to thank my mother, family and friends for their support, in particular my girlfriend *Antje* whose patience and support of my work has helped me through the more challenging times. In unlocking another door of perception, I hope that this PhD thesis represents the first step in transforming the unknowns into knowns in our understanding of perception and orientation in minimally invasive surgery.

I dedicate this thesis to the memory of my father, *Hans Gustav Södergren*, to whom I owe much of my academic success.

CONTENTS

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List of Acronyms

2D	Two-dimension(al)
3D	Three-dimension(al)
ASGBI	Association of Surgeons of Great Britain & Ireland
ASGE	American Society for Gastrointestinal Endoscopy
BHI	Black Hole Illusion
BP	Blood Pressure
CT	Computed Tomography
ECG	Electrocardiogram
EEG	Electroencephalography
ELITE	Endoscopic-Laparoscopic Interdisciplinary Training Entity
EMD	Earth Movers Distance
FPS	Frames Per Second
MRI	Magnetic Resonance Imaging
fMRI	Functional Magnetic Resonance Imaging
GB	Gallbladder
GI	Gastrointestinal
HZ	Hertz
ICA	Index of Cognitive Activity
IMU	Inertial Measurement Unit
HES	Hospital Episodes Statistics
HR	Heart Rate
HRV	Heart Rate Variability
HMM	Hidden Markov Model
LDA	Linear Discriminate Function Analysis
LGN	Lateral Geniculate Nucleus
MEMS	Micro Electro-Mechanical System
MIS	Minimally Invasive Surgery
MWU	Mann Whitney U Test
NNA	Nonlinear Neural Network Analysis
NOSCAR	Natural Orifice Consortium for Assessment and Research
NOTES	Natural Orifice Translumenal Endoscopic Surgery
PC	Personal Computer
PHC	Parahippocampal Cortex
PPRF	Paramedian Pontine Reticular Formation
RIN	Rostral Interstitial Nucleus
ROI	Region of Interest

RPE	Retinal Pigment Epithelium
RUQ	Right Upper Quadrant
SAGES	Society of American Gastrointestinal and Endoscopic Surgeons
SILS	Single Incision Laparoscopic Surgery
UK	United Kingdom
USA	United States of America
USB	Universal Serial Bus
USS	Ultrasound Scan
VOG	Video-Oculography
WWW	World Wide Web

Chapter 1 Introduction

Correct spatial orientation is paramount in everyday life and involves a goal directed interaction with the environment, and the knowledge of location within surroundings. Disorientation describes the process of deviating from the orientated state and reorientation involves the process of reversing this process to re-establish correct orientation. These paradigms have been the subject of considerable research and resource allocation within high risk, high-reliability systems and technology-driven operations such as the aviation, military, and racing industries. The subject is also of intense debate within the fields of cognitive processing and psychology. However, to date limited work has been undertaken to understand the factors and implications of this phenomenon in relation to surgery. One of the reasons for this lies in the intrinsic nature of the problem. Orientation is a subjective notion which is very difficult to describe, measure, and quantify. In addition to this, the effect of disorientation in surgery is complicated and often not assessed objectively. Another reason for the apparent lack of research into surgical disorientation is the relatively novel application of minimally invasive surgery (MIS). With the introduction of laparoscopic surgery came a number of additional factors which can potentially increase user disorientation, including a two-dimensional user interface with degradation in visual orientational cues, further complicated by the fulcrum effect produced by the instruments and decreased tactile and haptic feedback. As MIS evolves, single-incision laparoscopic surgery (SILS) and natural orifice translumenal endoscopic surgery (NOTES) promise to pose even greater problems of operator disorientation with a further decrease in orientational cues, yet with increased cognitive load and complexity of instrument navigation. Operator disorientation has been identified as one of the central issues that have to be resolved prior to the potential clinical adoption of NOTES.

It is important to try to prevent operator disorientation in MIS procedures, and theoretically there are several ways of doing this, including education and training of the surgeons and specific tools and devices to enhance or stabilize our perception of the operative environment. However, it is equally important to identify disorientation as it occurs and efficiently and correctly re-orientate when disorientated to ensure patient safety. Current data acknowledges the catastrophic role disorientation can play as a causative factor in surgical error but unlike other industries we have not allocated significant resources into the investigation of this concept. Furthermore, no methods of identifying, comparing, profiling and quantifying this behaviour have been developed at a collective or individual level.

To determine the best method of investigating perception, in particular orientation in MIS, it is therefore crucial to take into account broadly how this has been performed in other fields. A review of what is currently known about orientation looking specifically at research published in the aviation, psychology and virtual environment literatures is therefore outlined in Chapter 2. The importance and the underlying reasons for studying the visual system in perception are described and eye tracking techniques are introduced as a tool to assess the process of visual attention. Finally MIS as an emerging surgical subspecialty and a growing influence in abdominal surgery is reviewed focusing on the operation of laparoscopic cholecystectomy as an example of what is currently known about the likely effects of operator disorientation. This is related to the concept of human error and parallels are drawn between MIS and error perspectives in the aviation industry. Natural orifice surgery is the latest ideological advance in the field of MIS and its relatively short history as well as current applications is described. Current challenges that are hindering the widespread clinical adaptation of NOTES are discussed in the context of technological innovation to provide future solutions, and the specific reasons for the high risk of disorientation during flexible access procedures are outlined.

The first experimental protocol aimed at characterising patterns of orientation is described in Chapter 3. In this validation study, visual reorientation behaviour using eye tracking data in a simulated bench-top model is assessed using a fixation sequence similarity-based Markov model. The output of this algorithm is validated in terms of its reliability in differentiating visual behavioural sequences and the significance of the embedding is deduced at an individual level. The correlation of task performance and visual behaviour is explored in detail and effective behaviour is classified. The use of this method of analysis as a framework for future characterisation of orientation is defined.

The analysis framework presented in Chapter 3 is then used in the evaluation of orientation strategies of experienced gastrointestinal surgeons during specific stages of a laparoscopic cholecystectomy in Chapter 4. Here, visual behaviour is profiled as surgeons are presented with a disorientating image requiring reorientation. This investigation focuses on the importance of specific visual cues and successful orientation strategies for individual scenarios or operative stages are explored at a collective level. The idea of gaze plot analysis is introduced and laparoscopic experience is investigated as a factor for indicating orientation performance.

In defining successful orientation behaviour, the opportunity in using this information in an educational setting becomes apparent. Therefore, in Chapter 5 the possibility of teaching high performance orientation strategies to novices in laparoscopic surgery is explored. The impact of a focused procedure-specific multimedia tutorial is evaluated in a randomized controlled trial of final year medical students. To fully appreciate the significance and potential implications of the results, the outcomes were assessed not only by performance but also through profiling and comparison of the visual behaviour between the groups.

An evaluation of orientation strategies in clinical NOTES scenarios is investigated in Chapter 6. Due to the increased tendency for disorientation and additional visual cues such as trocars and endoscopes used during NOTES, the concept of normalizing visual attention by the saliency of the scene is introduced. Despite the lack of NOTES experts, high performance orientational behaviour is elicited using the previously validated analytical model. The relevance of the results in relation to the process of innovation and design to decrease disorientation in a NOTES operating platform are discussed.

In previous chapters, the method by which disorientation is induced is examined by transformation of the visual stimuli on the roll axis. In Chapter 7 automatic endoscopic horizon stabilization is investigated as a possibility to decrease the risk of disorientation due to this process in a randomized controlled trial of a NOTES procedure in a simulator model. Differences in performance between surgeon and gastroenterology specialists are investigated and the potential future use and modifications of this technology are highlighted.

The thesis is concluded in Chapter 8 with a summary of the major achievements and its potential limitations, as well as an outline of future research opportunities arising directly from the studies conducted in this thesis.

The major contributions of this thesis are as follows:

1. Identified a method by which orientation behaviour could be characterised, profiled, compared and quantified. This thesis represents the first detailed investigation into perception and orientation in MIS. As part of this thesis, it has been demonstrated that eye tracking is a valid and useful tool for the evaluation of psychophysical behaviour in the context of surgery.

2. Investigated specific orientation strategies associated with high performance outcomes at explicit stages of laparoscopic cholecystectomy. This is the first report of distinct orientation strategies employed by minimally invasive surgeons. We know that major morbidity during this operation is caused by surgeon disorientation and by focusing on particular stages of the procedure a detailed insight into temporal modification of behaviour can be gained.

3. Evaluated whether by identifying high performance psychophysical behaviour, the corresponding results could be used as an educational tool to increase performance of groups of individuals. This is the first report in the surgical literature which not only investigates learning of orientation strategies but also proves a significant benefit of their use in focused minimally invasive surgical teaching.

4. Investigated whether orientational behaviour could be classified and quantified in the context of natural orifice translumenal endoscopic surgery. NOTES operations are associated with a higher risk of disorientation. Despite the overwhelming consensus of the problem posed by spatial orientation in NOTES, this is the first description of orientation strategies in current clinical NOTES scenarios and introduces the concept of scene saliency to the reader.

5. Evaluated the use of automatic endoscopic horizon stabilization as applied to the conventional flexible endoscope during a NOTES task. This has been described as a potential tool to increase spatial orientation and is assessed in the context of a NOTES navigation and resection task.

Figure 1.1 below illustrates how the end goal of perceptual enhancement and orientation are investigated throughout this thesis starting with disorientation in MIS through the two pathways of laparoscopic applications and NOTES applications with identification of the relevant chapters in which each theme is investigated.

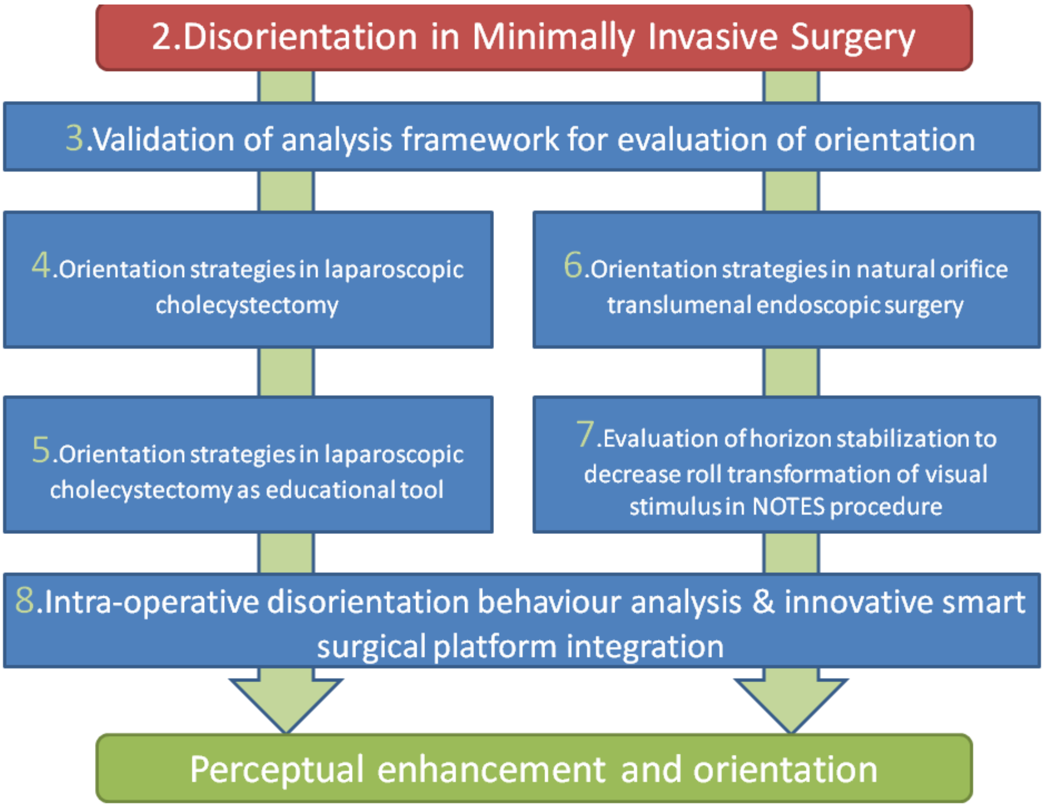

Figure 1.1 The structure of the thesis and relations between components illustrated graphically. Numbers in boxes indicate chapter number in which issue is primarily addressed.

The work presented in this thesis has resulted in the following publications in peer reviewed journals and presentations at international conferences:

Chapter 2

- Sodergren MH, Clark J, Athanasiou T, Teare J, Yang G-Z, Darzi A. Natural Orifice Translumenal Endoscopic Surgery: critical appraisal of applications in clinical practice. Surg Endosc. 2009 Apr; 23(4): 680-7.

- Sodergren MH, Coomber R, Clark J, Karimyan V, Athanasiou T, Teare J, Yang G-Z, Darzi A. What are the elements of safe gastrotomy closure in NOTES? A systematic review. Surg Innov. 2010 Dec;17(4):318-31

Chapter 3

- Sodergren MH, Orihuela-Espina F, Clark J, Darzi A, Yang G-Z. A model to characterise reorientation strategies in natural orifice translumenal endoscopic surgery. Cogn Process. 2009 Sept; 10(2): 307-11

- Sodergren MH, Orihuela-Espina F, Clark J, Darzi A, Yang G-Z. A hidden markov model-based analysis framework using eye-tracking data to characterise re-orientation strategies in minimally invasive surgery. Cogn Process. 2010 Aug;11(3):275-83.

- Sodergren MH, Orihuela-Espina F, Clark J, Darzi A, Yang G-Z. A model to characterise reorientation strategies in natural orifice translumenal endoscopic surgery. Oral presentation at the 4th International Conference on Spatial Cognition in Rome, Italy, October 2009

Chapter 4

- Sodergren MH, Orihuela-Espina F, Clark J, Teare J, Yang G-Z, Darzi A. Evaluation of orientation strategies in laparoscopic cholecystectomy. Ann Surg. 2010 Dec;252(6):1027-36

Chapter 5

- Sodergren MH, Orihuela-Espina F, Clark J, Teare J, Yang G-Z, Darzi A. Value of orientation training in laparoscopic cholecystectomy. Br J Surg. 2011 May 10 [Epub ahead of print]

- Sodergren MH, Orihuela-Espina F, Clark J, Teare J, Yang G-Z, Darzi A. Orientation training in laparoscopic cholecystectomy – a randomized controlled trial. Oral presentation at the Association of Surgeons of Great Britain and Ireland in Bournemouth, United Kingdom, May 2011

Chapter 6

- Sodergren MH, Orihuela-Espina F, Mountney P, Clark J, Teare J, Yang G-Z, Darzi A. Orientation strategies in Natural Orifice Translumenal Endoscopic Surgery. Ann Surg. 2011 *In press*

- Sodergren MH, Orihuela-Espina F, Mountney P, Clark J, Teare J, Yang G-Z, Darzi A. Orientation strategies in Natural Orifice Translumenal Endoscopic Surgery. Poster presentation at the Annual Scientific Congress of the Association of Laparoscopic Surgeons of Great Britain & Ireland in Nottingham, United Kingdom, November 2010

Chapter 7

- Sodergren MH, Warren A, Nehme J, Clark J, Gillen S, Feussner H, Teare J, Darzi A, Yang GZ. Endoscopic horizon stabilization in Natural Orifice Translumenal Endoscopic Surgery – a randomized controlled trial. Endoscopy. *Submitted*

Chapter 8

- Sodergren MH, Clark J, Yang G-Z, Darzi A. Natural Orifice Translumenal Endoscopic Surgery – safe implementation through technological innovation. Eur Surg. *In press*

- Sodergren MH, Yang G-Z, Darzi A. Perception and Orientation in Minimally Invasive Surgery. Surgery. *Submitted*

Chapter 2 Perceptual factors for orientation and their influence on minimally invasive surgery

2.1 Human Orientation

2.1.1 Orientation process

To evaluate the fundamental processes of disorientation and re-orientation with reference to MIS, it is important to understand the meaning of human spatial orientation and how these terms are related. Orientation in space is a vital feature of human and non-human animal survival and has been studied in great detail. Orientation is important in almost all essential human activities, from manoeuvring to destinations of choice to finding and consuming food essential for survival. This can normally be achieved with minimum effort under normal conditions. Orientation therefore involves goal-directed interaction with an environment [1] and the terms *orientation* and *re-orientation* are frequently used interchangeably. There is no detailed investigation or data in relation to orientation in MIS and therefore to evaluate this problem in a meaningful way, it is essential to understand the work done on this subject in other fields, particularly in psychology. Much of this theoretical understanding of orientation should be directly applicable to surgery and therefore should form a solid platform on which to initiate preliminary experimentation protocols.

2.1.2 Defining disorientation and re-orientation

Physical orientation is defined as determining an individual's location in their surroundings whilst mental orientation is a function of the mind, involving awareness in three dimensions; time, place and person. However, for the purposes of orientation in MIS we will on the whole only deal with awareness of place as disorientation in time, place and person are thankfully a very rare occurrence in MIS.

Disorientation and re-orientation are therefore processes involved in going to and from the orientated state. Problems with orientation lead to disorientation and the orientated state is re-gained after the process of successful re-orientation. Human and animal re-orientation has been extensively studied in the psychology literature and is closely linked to the concept of ‘place learning’ which will be described in detail in this chapter. Disorientation is defined as a cognitive disability in which the senses of time, direction and recognition become difficult to distinguish, however the main relevance here to MIS obviously involves recognition and direction.

2.2 Disorientation

There are several types of human disorientation described in the literature, including postural, temporal, spatial, auditory, vestibular, positional, and rotational. For a pilot, for instance, these factors can all work alone or in combination with others to produce disorientation. For the purposes of MIS though, postural, temporal, auditory and vestibular disorientation are less important contributing factors, as the main problems are associated with spatial disorientation.

2.2.1 Human sensory input and spatial disorientation

The human sensory inputs used for orientation in space are derived from the eyes, ears, muscle and skin. Good spatial orientation relies on effective perception, integration, and interpretation of visual, vestibular and proprioceptive sensory information. Visual reference provides the most important sensory information to maintain spatial orientation and this relationship is represented in Figure 2.1. The vestibular system is essentially a three-axis rate gyro system in the inner ear consisting of the vestibule, utricle, and saccule and it also contains three tubes called semi-circular canals. These tubes contain endo-lymph and hair cells. Nerve impulses generated by the hair cells indicate to the brain the direction of head movement. For the purposes of this thesis, vestibular end-organ function will not be discussed in any detail as it has limited relevance to disorientation in MIS.

Sensory input from stretch receptors located in the muscles and the joint-supporting ligaments provide a human with information of relative movements and position of neighbouring parts of the body and this has obvious relevance to instrumentation and haptic feedback in MIS. However to understand how perception of the operative scene is registered during MIS it is important to understand the visual system and in particular the anatomy, physiology and neurology interact to create an understanding of our environment.

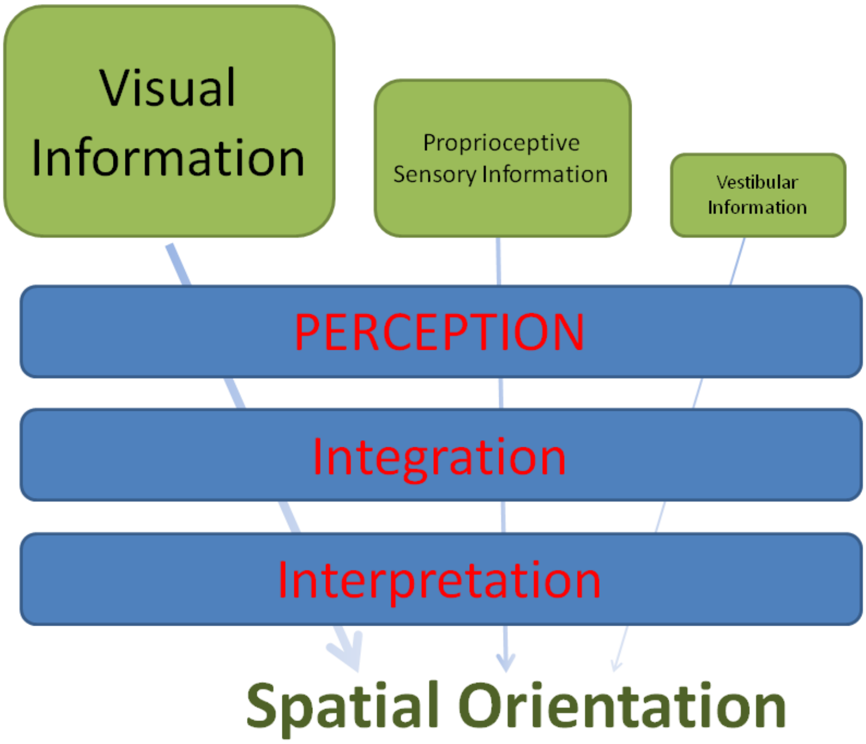

Figure 2.1 Illustration of the sensory input and subsequent processing involved in human orientation in MIS. Size of input highlights the importance of the visual system for this application.

2.3 The human eye

The eye and brain are the organs primarily responsible for vision and therefore the majority of sensory input during MIS, and the anatomy, physiology and topography will therefore be described herein in appropriate detail.

The eyeball is a sphere about 24mm in diameter consisting of the cornea (the prominent anterior segment), and the remaining large posterior segment which occupies five-sixths of the sphere; the sclera. The principal structures of the eye are shown in Figure 2.2. The wall of the eyeball comprises three distinct coats [2]:

- An outer fibrous coat consisting of sclera and cornea
- A middle vascular coat consisting of the choroid, ciliary body and iris
- An inner neural coat formed by the retina. Functionally it can be divided up into an outer pigmented cell layer and internal neural layer.

The retina is particularly significant in sensory input as it contains the visual receptors.

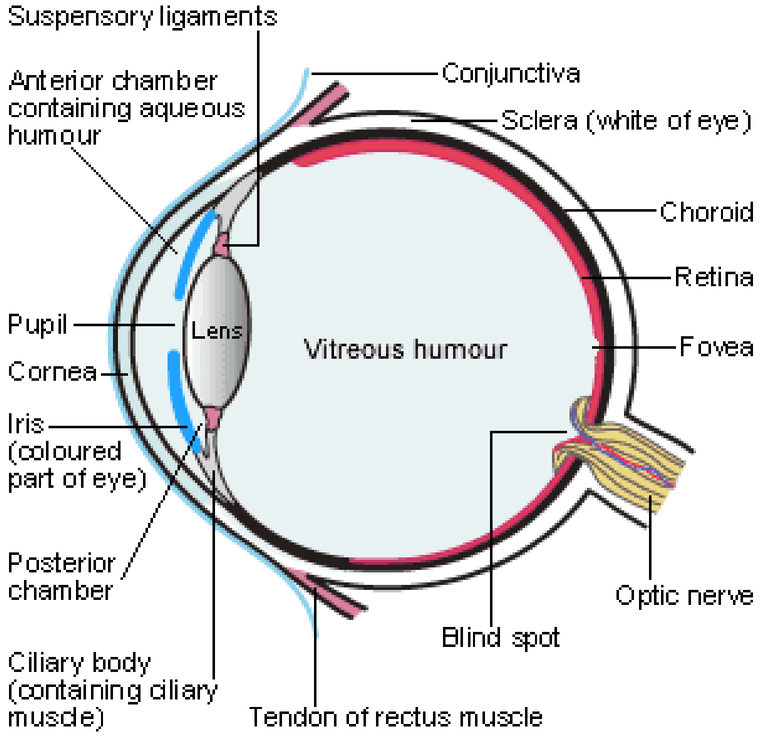

Figure 2.2 Principal structures of the eye [3]

2.3.1 The retina

Originally developed from the optic cup of the embryo, the retina has an outer and inner layer. The outer layer consists of pigmented epithelium and the inner layer of neural tissue in which the rod and cone cells are located. These cells are the visual receptors and work in conjunction with four types of neurones translating light to signals in the optic nerve: bipolar cells, ganglion cells, horizontal cells and amacrine cells. The rods and cones synapse with bipolar cells which in turn synapse with ganglion cells. The axons of the ganglion cells converge and leave the eye as the optic nerve. Horizontal cells connect receptor cells to one another in the outer plexiform layer and amacrine cells connect ganglion cells to one another in the inner plexiform layer [4].

Figure 2.3 illustrates the structure of the neural components of the retina

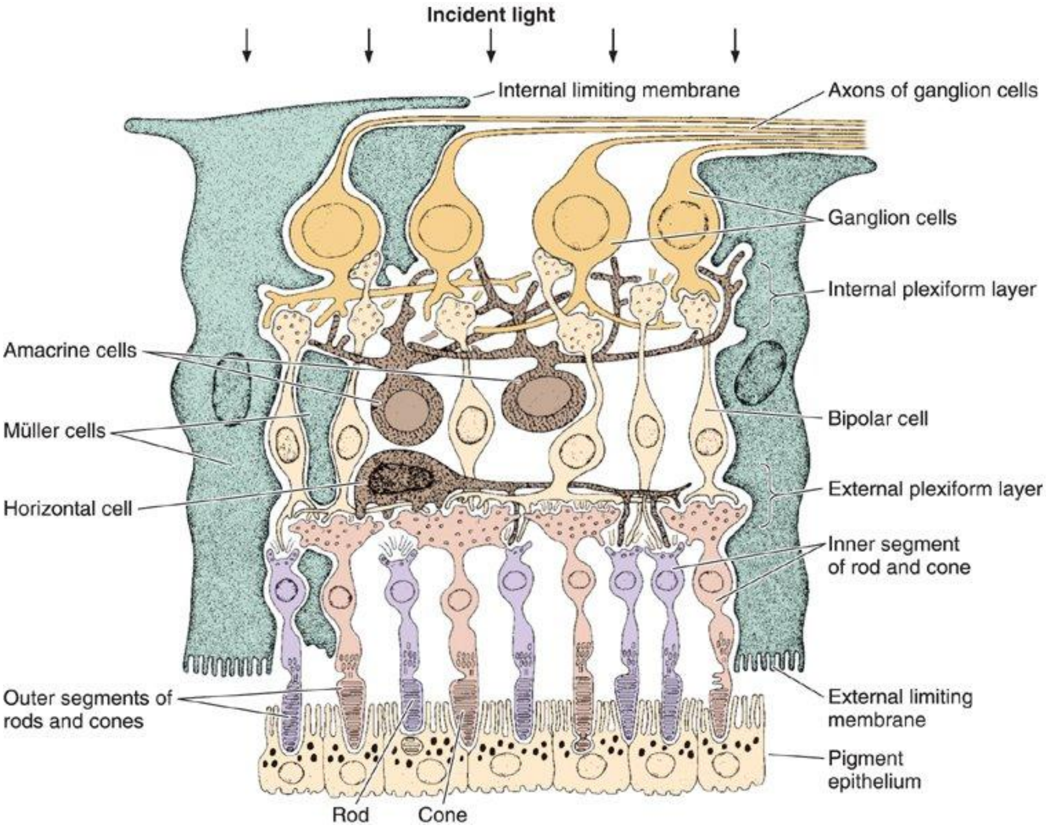

Figure 2.3 Neural components of retina [5]

Rods and cones are in part made up of stacks of flattened saccules or discs composed of membrane, which contains the photosensitive compound which reacts to light by initiating action potentials in the visual pathways. There are approximately 6 million cones and 120 million rods in each human eye. There are many more discs found in rods than in cones, which make them 100 times more sensitive to light. They are responsible for night vision and because of their location in the retina they are also concerned with our peripheral vision. The cones therefore have a high threshold to light energy and as such are responsible for sharp visual discriminations and colour vision [6], and are also concerned with foveal vision.

2.3.2 Foveal vision

Foveal vision is the most accurate part of human vision and represents approximately the central 2 degrees of the visual field. The fovea is the part of the retina in which there are only cones, with few other cells or blood vessels overlying the receptors and is the point where visual acuity is the greatest. When humans turn their attention to an object, the eyes are normally moved so that the light rays coming from that object fall on the fovea [6]. This results in a fixation on that object within the scene.

2.3.3 Peripheral vision

Peripheral or ambient vision is the part of vision that occurs outside the central or foveal vision and is associated with the perception of movement (a feature of rod cells) of either one self or the environment. In MIS its importance lies most in navigation within the spatial environment, and during orientation eye movement is controlled by the extra-ocular muscles.

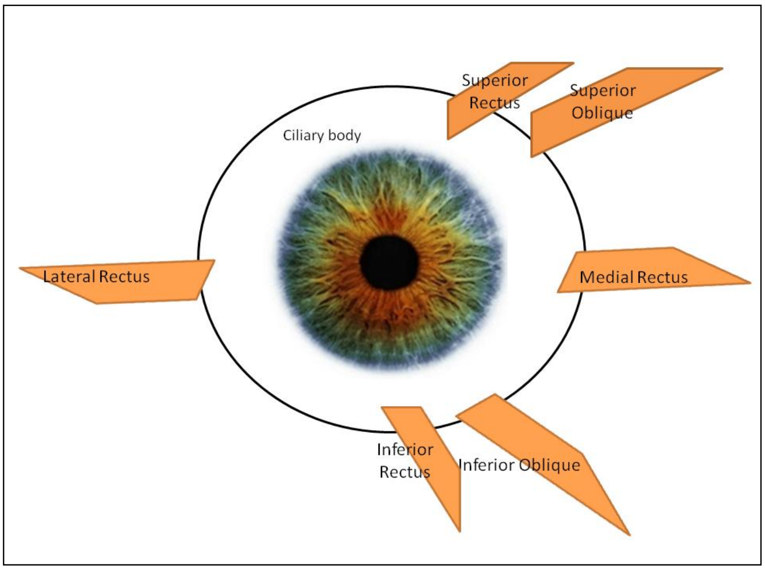

Figure 2.4 Principle extra-ocular muscles and direction of contraction of right eye

2.4 Eye movements

The eye has six degrees of freedom and is capable of movements along horizontal, vertical and torsional axes. Eye movements are controlled by three antagonistic pairs of extra-ocular muscles comprised of the superior and inferior recti, the medial and lateral recti, and superior and inferior oblique as illustrated in Figure 2.4. These are innervated by cranial nerves III (oculomotor), IV (trochlear), and VI (abducent) [7,8]. These muscles produce all movements of the eye. There are 6 main classes of eye movements described, the understanding of which are vital in the meaningful interpretation of data derived from eye tracking techniques:

2.4.1 Saccadic

These are quick, simultaneous movements of both eyes in the same direction with peak angular speeds of up to 700°/s. Saccades are the fastest movements produced by the human body. Their main purpose is to reposition the fovea to a new location in the visual environment. These movements can be voluntary or they can form part of corrective optokinetic or vestibular measure. The duration of saccades varies from 10ms to 100ms. There are two important issues associated with fixating the eye on a new target in space: controlling the amplitude and the direction of the eye movements. The amplitude of a saccadic eye movement is encoded by the duration of neuronal activity in the lower motor neurons of the oculomotor nuclei [9].

The direction of the movement is determined by which eye muscles are activated and the directions of eye movements are controlled by the local circuit neurons in two gaze centres in the reticular formation. The paramedian pontine reticular formation (PPRF) or horizontal gaze centre is located near the midline in the pons and is responsible for generating horizontal eye movements. The rostral interstitial nucleus (RIN) or vertical gaze centre is located in the rostral part of the midbrain reticular formation and is responsible for vertical movements. Activation of each gaze centre separately results in movements of the eyes along a single axis, either horizontal or vertical although more complex oblique movements are a result of relative complementary activation of both gaze centres, depending on the precise movement required [9].

2.4.2 Smooth pursuits

These eye movements represent the ability of the eye to smoothly follow a moving target, and the second way in which animals are able to shift their point of fixation. The eyes are able to match the velocity of a moving target up to a velocity of about 30°/s visual angle.

2.4.3 Miniature eye movements

Fixations are the times when the eyes are relatively steady and it is during this time that virtually all visual / sensory input occurs. Fixations are defined as a brief period of time (e.g., > 100ms) where the point of focus of the eye is relatively stationary and represents a span of time where the user's attention is fixated on a discrete portion of the visual stimulus. If a subject is asked to maintain fixation on a particular target, his eyes will make consistent but idiosyncratic pattern of slow and fast movements [10]. These are miniature eye movements. These were first described by Steinman et al and are comprised of three distinct movements: tremors (physiological nystagmus), drifts and microsaccades. These movements are complicated and their purpose have been the topic of much debate however it appears their main function is to maintain the point of fixation to enhance fine spatial detail [11] as well as preventing the visual scene from fading [12].

2.4.4 Optokinetic nystagmus

Optokinetic nystagmus is a mostly involuntary smooth pursuit movement interspersed with saccades. The main purpose of this is to compensate for retinal movement of a target and is characterized by a saw-tooth ocular movement of up to 2° at about 30°/s about the horizontal or vertical axis of the eye [13].

2.4.5 Vestibulo-ocular

The aim of this eye movement (vestibule-ocular reflex) is to stabilise images on the retina during head movement by producing an eye movement in the direction opposite to head movement, keeping the image on the centre of the visual field. The sensory input from this comes from the semicircular canals and otoliths in the inner ear which detect translational movements of the head [14]. When this is recorded during eye tracking the point of regard is obviously stationary so unless subject movements are recorded these are rarely registered and have same significance as a fixation.

2.4.6 Vergence

Vergence movements are responsible for convergence and divergence of the eyes, thereby changing the angle between the eyes. An example of this is when if you are looking at your finger in front of your nose and move it away from and towards your face, whilst fixating on the tip. These movements counter-rotate the eyes to maintain images of an object at a given depth to be projected to the appropriate position of two retinae [15]. Again when this is recorded using eye tracking it will register as a fixation, which corresponds to the higher cortical intention.

2.5 Neural coding of vision

As the eyes move to fixate on specific features in a scene, the primary purpose of this is to gain sensory information about the environment. This information is interpreted by the brain through the neural coding of vision. As the optic nerves leave the orbits they meet at the optic chiasm where fibres from the nasal halves of each retina cross to the opposite side of the brain, while those from the temporal halves remain uncrossed. This partial decussation is called the chiasma and nerve fibres then continue in one of the optic tracts. Each optic tract terminates in a sensory relay nucleus, the lateral geniculate nucleus (LGN) in the thalamus. The neurons of the LGN then relay the visual image to the primary visual cortex which is located in the occipital lobe of the brain [6].

2.5.1 Neural coding and topographical disorientation

As the sensory information of the visual system is integrated in the brain with other sensory systems and processed outside of the visual cortex, several key areas in the brain described below have been implicated with disorientation. These are likely to have relevance in future evaluation and solutions to disorientation in MIS. It is known that topographical disorientation can be acquired from lesions to different cerebral regions participating in the attentional, perceptual or memory functions involved during navigation. Topographically an area of the brain called the parahippocampal cortex (PHC) has been implicated with disorientation and patients who have had strokes of the mediotemporooccipital lobe have shown clinical impairments in allocentric and egocentric spatial orientation [16]. Wilson et al reported a case of egocentric disorientation following bilateral parietal lobe damage [17] and Morganti et al presented a patient with a right medial temporal lobe lesion who showed a selective impairment in the acquisition of new spatial relationships as evidenced by her performance in the "planning in advance task" in a virtual environment compared to normal controls [18]. Similarly, Iaria et al showed that a patient with topographical disorientation in the absence of any structural lesion and with intact sensory and intellectual function had decreased activation of the hippocampal complex and the retrosplenial cortex on functional magnetic resonance imaging (fMRI) compared to healthy control subjects [19]. This study therefore suggests that topographical disorientation can occur as a result of a developmental defect and this can be clinically and anatomically correlated.

2.6 Visual cues and references

When orientating in any environment humans use a variety of visual cues which have varying levels of significance. The qualities and attributes of visual cues are likely to be particularly significant in MIS and can be broadly divided into two categories [20]:

1. Geometric cues are defined by extended environmental surfaces, such as the shape formed by room walls or undulating terrain.
2. Featural cues are non-geometric cues, such as colours and texture, which cannot be defined by geometry alone.

Visual references that provide information about distance, speed, and depth of visualised objects include:

- Comparative size of known objects at different distances.
- Comparative form or shape of known objects at different distances.
- Relative velocity of images moving across the retina. Nearby objects are perceived as moving faster than distant objects .
- Interposition of known objects. One object placed in front of another is perceived as being closer to the observer.
- Varying texture or contrast of known objects at different distances. Object detail and contrast are lost with distance.
- Differences in illumination perspective of objects due to light and shadows.
- Direction of movement of substances such as liquid and smoke provide orientational cues provided the configuration of the reference scenery is known

These all play an important part in maintaining or regaining orientation in MIS and a number of non-visual cues are also important including haptic feedback.

2.7 Visual attention

To gain a greater understanding of orientation in MIS, it is necessary to consider psychological principles and assumptions that underpin attention. In the theory of cognition, visual search is considered a type of perceptual task requiring attention. Visual search involves an active scan of the visual environment for targets or features. In everyday life, this may involve finding the desired book on a library shelf or finding one's preferred sweet in a packet [21]. Attention refers to the cognitive process of selectively concentrating on one thing while ignoring other things. This has been very eloquently described by an eminent psychologist, William James as quoted below [22]:

"Everyone knows what attention is. It is the taking possession by the mind in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought... It implies withdrawal from some things in order to deal effectively with others."

To obtain specific sensory information about our environment, we have to focus our senses on that particular feature, therefore, the notion of focus of attention has a derived meaning referring to the physically observable behaviour of orientation towards an object. This may take the form of posture, head orientation and/or gaze. Gaze direction can therefore be used as an indicator of attention in a visual environment. It is now widely accepted that distribution of eye fixations is mostly governed by intention and can therefore be related to attention [23] provided that the eye movement is task-relevant as defined by Kahneman [24]. Eye-tracking can therefore provide data on a subject's visual search patterns and therefore an indication of visual attention provided the correct experimental conditions are met. Because attention is composed of both higher and lower level functions, it is well known that humans can voluntarily dissociate attention from their foveal direction of gaze [25]. This high level component of vision is obviously much more difficult to detect by objective external observation. Therefore, the important assumption that attention is linked to foveal point of gaze is usually made in eye-tracking experiments, but it is acknowledged that this may not always be the case.

2.7.1 Attention control

Studies about human visual perception show that visual attention selection is driven by two types of attentional mechanisms: top-down and bottom-up. Top-down signals are derived from task specification, while bottom-up signals are caused by salient stimuli. Recent work by Buschman et al has suggested that top-down signals arise from the frontal cortex and bottom-up signals arise from the sensory cortex in primates [26]. It is important to discriminate between these two mechanisms as they are likely to result in very different outcomes when applied to behaviour such as orientation. It seems likely that top-down signals are indicative of a strategy, goal and specific problem-based approach when considered in the context of disorientation and one would suggest that this is favourable to a bottom-up approach however to date there is no evidence to support this.

2.8 Eye tracking

As eye fixations can be inferred to be directly related to attention and therefore underlying thought processes or higher cognitive functions, it seems appropriate to use eye tracking as a principal tool in the investigation of perception as applied to MIS. Eye tracking is the process of recording points of gaze and the primary instrument used for the investigation and assessment of perception and orientation throughout this thesis.

There are currently three techniques for measuring eye movements: electo-oculography, scleral contact lens/ search coils, and techniques based on reflected light such as video-oculography (VOG) [27]. It is worth briefly describing all three techniques to put eye tracking research into context:

2.8.1 Electo-oculography

This technique works by measuring the resting potential of the retina. Usually, pairs of electrodes are positioned around the eye (above and below or to the left and right). When the eye moves towards an electrode, the retinal pigment epithelium (RPE) generates a potential difference between the electrodes, and if the resting potential is assumed to be constant, the recorded position is a measure of eye position. Since this method measures eye movements relative to head position, the head position has to be measured to assess points of gaze.

2.8.2 Scleral contact lens / search coils

This method of measuring eye movements involves attaching a mechanical or optical reference object mounted on a contact lens worn directly on the eye. One of the most popular devices employs a wire coil, which is then measured moving through an electo-magnetic field. With an accuracy of around 5-10 arc/seconds over a limited range of about 5°, this is the most precise method of detecting eye movements [28]. The disadvantage lies in its invasive nature and that this method also measures eye movements relative to the head.

2.8.3 Video-oculography

Video-oculography (VOG) is now the most commonly used method in eye tracking research for measuring eye movements and is the method used for the experiments in this thesis. VOG utilises cameras and image processing hardware to compute point of regard in real time by measuring distinguishable features of the eye under rotation and translation. The systems can be either table- or head-mounted. They work by measuring the corneal reflection of the infra-red light source relative to the centre of the pupil. These corneal reflections are known as Purkinje reflections [29]. Since multiple ocular features (which remain constant) are measured, the head does not have to be in a fixed position to measure points of gaze.

2.8.4 Eye-tracking research in medicine

Initial studies of eye-tracking in medicine have involved analysing scan-paths of clinicians examining radiographs to determine the nature of errors that occurred. Kundel et al used eye-tracking to prove that there were 30% of false-negative errors when detecting pulmonary nodules on x-ray images [30]. Using the results of the experiment, they developed a model for nodule detection which involved four steps: orientation, scanning, pattern-recognition and decision-making. Similarly, recent scan-path experiments investigating cross-specialty visual search behaviour when examining skeletal radiographs for fractures have characterised the basic search strategies employed by experts in terms of broad areas of attention [31]. Similar results have been described in the evaluation of mammograms by expert mammographers and trainees [32].These experiments not only provide valuable data on high performance behaviour but also have wider implications within medical education and training.

More recently, eye tracking has been used in skills assessment and discrimination in MIS. Wilson et al [33] investigated how dwell time on target locations during a laparoscopic surgery simulation task on the LapMentor (Symbionix USA Corp., Cleveland, OH, USA) were correlated to operator experience. They found that experienced surgeons spent significantly more time fixating the target locations than novices, who spent more time tracking the tools with their gaze. Kocak et al [34] used a similar experimental task on a laparoscopic training station to measure more complex eye motion parameters such as saccadic rate, standardized peak velocity, standardized saccadic amplitude as well as fixation duration. They found some statistically significant differences in these parameters between surgeons of different levels of experience. Similar experimental paradigms have been used to differentiate skill level in aviation. Schriver et al [35] demonstrated that in a flight simulator scenario involving correction of an error, eye tracking can be used to discriminate between pilot experience levels. They found that expert pilots allocated a greater amount of attention as represented by percentage dwell time per region of interest to relevant cues when a failure was present and furthermore the amount of attention to cues was associated with decision accuracy.

However, for surgical applications, the study by Richstone et al [36] is perhaps the most significant and elegant evaluation of eye tracking as an assessment tool to discriminate between surgical skill of the operator. They also recorded a number of eye tracking metrics including blink rate, fixation rate, index of cognitive activity (ICA) and vergence. They used linear discriminate function analysis (LDA) and nonlinear neural network analysis (NNA) to classify surgeon by expertise as well as illustrating a correlation with changes in performance of novices in a longitudinal experiment. To date, eye tracking data has not been used in the behavioural evaluation of perception or disorientation within medicine or surgery.

2.8.5 Eye-tracking research and disorientation

Basic eye-tracking data has been used to evaluate disorientation in pilots. Cheung et al [37] used an integrated physiological trainer with interactive aircraft controls to assess performance degradation during disorientation in simulated flight. They found significant differences on a number of scanning behaviours, including number of saccades, and fixation duration and frequency on the designated display instruments between disorientating and control conditions. They also repeated this experiment to examine physiological 'markers' of disorientation and found that there was a significant increase in heart rate (HR), HR variability, and mean arterial blood pressure (BP) during disorientation [38]. These were all associated with a degradation of performance in the flight simulator. With regards to the eye tracking signal, this research has only focused on simple analysis of basic eye tracking parameters and some correlation to basic non-specific physiological markers with no evaluation of attention allocation and higher cortical behavioural patterns. Although there is no research base in relation to disorientation in MIS it is worthwhile reviewing the disorientation literature in psychology and the aviation industry to gain a more comprehensive understanding of disorientation and its potential role in MIS.

2.9 Disorientation research and the aviation industry

Pilot disorientation is known to be a contributing factor to some aviation disasters and as such a lot of resources have been devoted to studying this phenomenon. Statistics show that between 5 to 10% of all general aviation accidents can be attributed to spatial disorientation, 90% of which are fatal [39].

Gibb reviewed a particular type of visual spatial disorientation experienced by pilots called the "black-hole illusion" (BHI). This occurs when pilots attempt to land at night when the outside view lacks cues to the terrain around the lighted runway. This often leads to pilot disorientation and an inappropriate angle of descent. The following causes of spatial disorientation were found in the review: constancy of apparent size-shape-depth; conflict between familiar and relative size; overestimation of visual angles in the medial extent; deficient terrain orientation cues; lack of distance cues; disparity between optical and geographical slant; perception of approach lighting systems; tendency toward equidistance; and misperception of slant [40]. This has particular relevance to MIS as problems with inadequate peripheral illumination outside the operative field are not infrequent, and may in fact play an increased role as operations are carried out using illumination from flexible endoscopes outside the relatively small constraints of the gastrointestinal (GI) tract. The same group published a separate study concluding that approach lights lateral to the runway may counter BHI, the addition of random terrain objects failed to improve performance and surprisingly it appeared that novice pilots flew more stable approaches [41].

The aviation industry has also developed a number of aides to decrease pilot disorientation including advanced cockpit displays, elaborate structured simulator and real flight training programmes, tactile displays [42], and multisensory cueing systems [43].

2.10 Disorientation research and the psychology literature

The psychology literature states that a person is thought to be orientated by the ability to determine his/her location and heading relative to the surrounding environment [20]. When an individual is disorientated experiments have shown that the accuracy by which one can point to specific objects and landmarks in the environment without vision is substantially reduced and the behaviour is essentially random [44]. There is no reason why this is not directly applicable to MIS. The psychology literature considers two distinct types of disorientation:

1. Global disorientation represents disorientation with regards to the overall environment, for instance being unable to orientate which road one is driving on in a city.
2. Local disorientation, which represents disorientation with regards to one's immediate environment, for instance not being unable to identify the correct exit when driving down a road.

The process of becoming disorientated is poorly understood, however studies by Sargent et al [45,46] investigated this by subjecting participants to increasing levels of disorientation in the form of blind-folded whole body rotations around a fixed vertical axis. Subjects then had to indicate their heading at the start of the most recent or current series of turns. The results have indicated that this is a gradual process up to a threshold where a subject is "completely disorientated" [45]. This is noteworthy since if it can be confidently established that this is not a binary process then there are likely more stages at which the process can be reversed i.e. a greater widow of opportunity for intervention.

2.10.1 Frames of reference

The concept of frames of reference is an important one in the psychology literature and it has significant implications for MIS as technology has the ability to alter or aid in the processing of a particular frame of reference. To maintain orientation during navigation, spatial information has to be processed within a frame of reference. There are two described frames of reference within which objects are encoded during navigation [46]:

1. Within an allocentric frame of reference locations of significant objects are encoded relative to each other and in relation to other external, environmental references.
2. In an egocentric frame of reference objects are encoded relative to oneself.

Previous studies have indicated the use of both egocentric and allocentric frames of reference in humans [47-49] and it is generally thought that both representational systems play a role in human orientation and navigation [46], with large individual and gender variability. Gramann et al investigated different strategies in spatial navigation during passages through computer-simulated tunnels by means of electroencephalography (EEG) source reconstruction [50] . The tunnels consisted of straight and curved segments and provided only visual flow, but no landmark information. At the end of each tunnel passage, subjects had to indicate their end position relative to the starting point of the tunnel. They identified two distinct subject groups: one group using allocentric and the other using an egocentric reference frame. For both strategy groups, an occipito-temporal network was dominantly active during the initial, straight tunnel segment. For subjects with an egocentric reference frame there was prevailing activity within a posterior parietal-premotor network, with additional activity in frontal areas. Computation of an allocentric reference frame was associated with dominant activity within an occipito-temporal network, confirming right-temporal structures to play a crucial role for an allocentric representation of space [50]. This experimental set-up bears obvious resemblance to complex and disorientating navigational conditions encountered by endo-laparoscopic surgeons and perhaps serves as a benchmark for future topographical investigations of disorientation in MIS.

Kelly et al explored the importance of various spatial cues in maintaining orientation [51]. Subjects performed a spatial updating task within a virtual environment containing geometric or featural cues that were ambiguous or unambiguous indicators of self-location and direction. They found that cue type (geometric or featural) did not affect performance, however the number of environmental cues and the ambiguity of those cues did affect performance. Again, gender differences were noted. When only one environmental cue type was available, whether featural or geometric, men stayed orientated whilst women did not.

2.10.2 Path integration

This is the process by which internal self-motion cues such as proprioception and external cues such as optic and acoustic flow are integrated over time. Path integration together with environmental cues is key in determining spatial orientation. Disorientation eliminates path integration with an obvious degradation in navigational performance. For the purposes of this thesis, it is important to bear this concept in mind during evaluation of individual behaviour although as mentioned, the overwhelming majority of sensory input comes from the visual system.

2.10.3 Cognitive map

This term was coined by Edward Tolman in 1948 and represents the integration of perceptual stimuli into an internal, consistent representation of the environment [52]. Downs and Stea referred to the cognitive map as “an incomplete, segmented, metrically distorted representation, with relational accuracy, both spatially and non-spatially varying within and across regions" [53]. As an individual becomes more familiar with an environment the reliance on external stimuli gradually decreases [54]. This is a significant concept when considering these psychological theories in the context of surgery as the cognitive map is often the surgeon’s local anatomical knowledge and alone can be a causative factor in disorientation or the key to avoiding it.

2.11 Cognitive impairment of spatial disorientation

It is important to establish that spatial disorientation does affect cognition and also under what circumstances cognitive impairment is likely to be more pronounced. Gresty et al [55] investigated how spatial disorientation may affect cognitive impairment by disorientating subjects using self controlled head rolls, rotation of the background field of view, and after head movements provoking Coriolis during body rotation in yaw. They used the Manikin test and Choice Reaction Time test as markers of cognitive function and concluded the ability to maintain a high level of cognitive performance is susceptible to impairment when novel circumstances of disorientation are encountered and that extensive practice on particular tasks protects against encounters with novel disorientation. By implication therefore practice or experience in certain operations are likely to confer an advantage when faced by disorientating future operations. However the reasons behind this are unclear and we certainly do not know what higher cortical functions such as strategies are gained through operative experience. It has therefore been proven that spatial disorientation can lead to cognitive impairment and we have objective instruments to measure cognitive impairment; however quantifying or measuring disorientation has proven more complex.

2.12 Measuring disorientation

One of the reasons why it is difficult to judge the success of methods to decrease disorientation is because of the complexity of accurately assessing and measuring this phenomenon. Four rudimentary methods have been previously used:

Firstly, user feedback seems to be a logical way of quantifying disorientation. It is vital to ask the correct question within the contextual environment to adequately gauge subject disorientation. Another important consideration is how to quantify this. Visual analogue scales are widely used in subjective research however these have never been formally validated with regards to disorientation.

The second method is examining the conceptual model developed by the individual using the assumption that the more accurate the model the less disorientated the individual is. This may be applicable to disorientation in surgery by for instance, asking subjects to draw a representation of the anatomy as they understand it.

The third method is measuring performance of the subject. When an individual is disorientated this will normally lead to a degradation of performance and this should be related to the degree of disorientation. One of the most common parameters used is time taken to complete a set task. This works on the assumption that individuals who are disorientated will spend more time trying to re-orientate themselves when completing a task. Another useful parameter would be measuring errors made by the subject. Examining "damage caused" represents another potential way of quantifying disorientation however this is highly dependent on the accuracy expected and also on context. For example when landing a plane a small error could have disastrous effects however a small error in another context may not have such severe consequences. The problem when using these outcome parameters in surgical applications is the assumption that disorientation is the main factor which influences outcome. It is therefore difficult to assess what other confounding factors have an effect on these outcome parameters as well as the extent of this effect.

Finally, measuring how the protagonist is affected when finding himself disorientated. As demonstrated by Cheung et al [38] some physiological parameters such as HR and HR variability (HRV) may be directly related to degree of disorientation. It would appear that this is also highly related to context as being disorientated when navigating the internet may not provoke the same physiological response as a pilot being disorientated during landing or a surgeon during a delicate part of an operation.

Yatim investigated a combination measurement for studying disorientation in subjects navigating the World Wide Web (WWW). He proposed a model whereby three elements are included in combination to measure disorientation [56]:

- Time taken to complete a task
- Accuracy (of answers), and
- How often subjects experience symptoms of disorientation

2.13 Reorientation

Having reviewed the concept of disorientation it is perhaps equally, if not more important, in MIS to understand reorientation, which is the basic animal adaptive strategy involving the ability to reverse the process of disorientation.

2.13.1 Reorientation research and the psychology literature

One of the first and most powerful experiments of orientation was described by Cheng in 1986 [57]. In this study, rats were trained to find food in a corner of a rectangular enclosure. The correct location was defined by the availability of geometric properties of the surfaces and non-geometric properties (visual and olfactory cues). The rats were then passively disorientated outside the enclosure, and when re-introduced Cheng found that they did not resort to featural cues when choosing where to search for the food, even though half their choices were wrong, thereby confirming the primary role of geometric information in reorientation. If they had combined the two sources of information this would have led them to the right choice. Hermer and Spelke reproduced the same results in 18 to 24 month old children [58].

However when the same hypothesis was tested in adult humans, they found that adults were able to use geometric cues alone if necessary and a combination of both non-geometric and geometric cues for successful reorientation [59]. They suggested that the development of spatial language was instrumental in being able to integrate featural and geometric cues. This was further supported by an experiment that showed that when humans were required to perform a reorientation task at the same time as a verbal shadowing task, thereby preventing the use of verbal language, human adults displayed the same pattern of errors as children in integrating geometric and non-geometric information [60]. In addition to this there is evidence to suggest humans change relative use of geometric and featural cues dependent on the size of the environmental space in which reorientation is examined [61]. There is no evidence to indicate the importance of featural or geometric cues in MIS however this knowledge would presumably be very useful in the design of platforms to decrease disorientation.

2.13.2 Modularity

In the study of theoretical psychology there exists a concept called modularity, which likely has high relevance to disorientation and particularly the role of disorientation in the context of error in MIS. This was first described by Jerry Fodor in 1983 [62]. He argued that our "input systems", such as our visual system, are modular. These parts of our mind are dedicated information processors, whose internal make-up is inaccessible to other related processors. These modular detection systems feed output to a central system, a kind of inference engine which Fodor did not believe was modular. There are conflicting views here, and other modularity theories have been presented that suggest that the central system is indeed modular too [63]. The massive modularity theory is about the source of our cognitive architecture and is the result of natural selection acting to produce each of the many modules. Our cognitive architecture is composed of innate computational devices or modules, and this architecture accounts for all of our sophisticated behaviour [63].

When considering reorientation, it is highly likely that the visual system is modular in nature [64], however it is unclear whether there is modularity in learning geometric and featural cues or if there is central modularity concerned with this process. Cheng and Newcombe [65] summarised the views on modularity in reorientation in Figure 2.5. Here the input system consists of perceptual and learning processes and some modularity in processing geometric and featural information is assumed. The central system relevant to reorientation tasks is labelled as "memory". In the impenetrable module (A), featural information does not enter into the memory system at all and if used goes through other central modules. In a system with modular memorial subcomponents (B), the main process contains only geometric information but featural information may be used in addition (represented by arrows inside memory box). In a modular input system only (C), geometric and featural information are integrated for reorientation tasks.

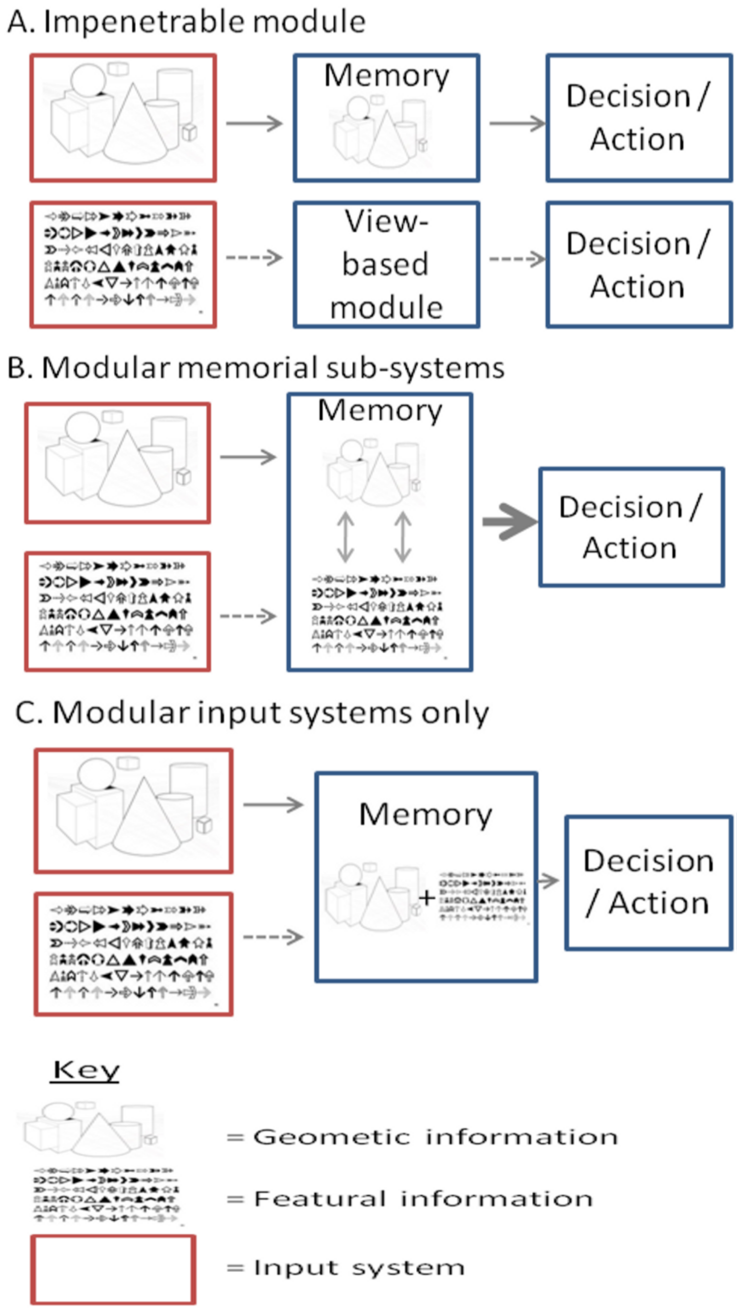

Figure 2.5 View on modularity in reorientation adapted from Cheng and Newcombe [65]. Current evidence does not confidently allow us to discriminate between these proposed theories and further research is necessary to clarify the significance of modularity in human reorientation tasks.

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2.13.3 Place learning

Closely related to the process of reorientation is the information used by animals to form place memories, a process called 'place learning'. This is essentially the acquisition of spatial information supporting navigation, and is a concept highly relevant to MIS. It has been suggested that this process if governed by a specialised system located in the hippocampus. It creates and maintains a unified map-like representation of the environment in which the spatial relationships among the features of the environment are preserved, and therefore from this cognitive map, information such as new trajectories to a goal location can be calculated. Whenever there is a mismatch between the current and stored perception, by exploring the environment, features will be added and deleted from the map [66].

One of the most important experiments in place learning was carried out by Morris in 1981 [67]. He showed that rats rapidly learn to find a target hidden just beneath the surface of opaque water in a large swimming pool and they directly approach the location of the hidden object even if their initial starting position is varied. This implies that the rats can locate the object based exclusively on distal room cues within the fixed spatial environment. An important aspect of these results is the emphasis between distal and proximal spatial orientation. Proximal orientation requires only localised cues coming from a stimulus and under these conditions the only necessary action is to generate a motor response towards these cues [68].

Jacobs et al have investigated place learning in humans in a virtual space environment [69]. They showed that in virtual space, humans learn to find an invisible target that remains in a fixed position relative to distal cues and that even though starting position varied, people would still directly approach the location of the invisible target based on the location of distal cues. In further work they showed that removing a full set of distal stimuli disrupted place performance but removing subsets did not, and that changes in topographical relations among the distal stimuli disrupted performance [70].

2.14 Orientation research in virtual environments

Research of orientation in virtual environments has obvious relevance to MIS as many of the associated conditions are similar with a two-dimensional user interface eliminating inertial cues such as the vestibular or auditory system.

Bosco et al investigated human reorientation ability inside virtual reality environments [71]. They showed that shortening the time period between the disorientation and the test phase (retention interval) did not influence performance when only geometric information was present to the subjects. Conversely, when both geometric and featural information was available, shortening the retention interval increased performance. They concluded that geometric cues seem to be encoded steadily in memory, whilst landmark cues seem less robustly encoded in memory.
Smith and Marsh evaluated the effect on disorientation of placement of objects in the virtual environment such that there is always one or more object partially in the user's field of view – 'the partially out of frame' guideline. These were represented by pictures, picture frames, wall panels and dado rails mounted along the walls of a virtual corridor during a navigation task. They showed that the implementation of these guidelines decreased user disorientation [72].

Harrower and Sheesley explored the idea of reducing user disorientation in the virtual environment of fly-over maps by introducing orientation cues and comparing this to the automatic navigation of the same terrain with no additional orientational cues [73]. Performance was assessed by evaluating the subjects' perceived path, which they drew. They found that introducing a monorail cue, which directly depicts the path of the viewer offering a preview of where they are heading next, halved user directional error. Introducing a landscape grid, providing both direction cues and a structuring framework, also halved directional error. The most effective cue was the horizon compass, which provided a directional feedback via a floating compass visible in the middle of the screen, which virtually eliminated directional error. However, using landmark labels as orientational cues was found to be ineffective and resulted in similar or worse performance than the map which had no orientational cues.

Picucci and Bosco examined the effect of geometric and featural cues on the reorientation paradigm in a virtual environment using a searching task [74]. The virtual environment was characterised by a) layout information only (geometric), b) landmark information only (featural) and a combination of both cues. They found that integration of geometric and landmark information is more demanding than landmark information alone, however they do point out that in their experimental scenario landmark information holds implicit geometric information by the relation between target and landmark. They conclude that integration of cues is achievable only under specific conditions, and that geometric and featural cues may compete in guiding spatial navigational tasks.

2.15 Perceptual factors in minimally invasive abdominal surgery

2.15.1 Spatial environment in minimally invasive surgery

As orientation is described as a goal-directed interaction with the environment, for the purposes of this thesis it is important to define the exact environment within which the operator works and the processes that are taking place.

2.15.2 Laparoscopic surgery

The earliest known attempt to look inside a human body date back from 460 to 374 BC from the Kos school of medicine led by Hippocrates in Greece, who used a speculum to examine the rectum. In 1879 the German Maximilian Nitze described the use of the first functional cystoscope thereby initiating modern endoscopy as we know it [75]. In 1901, the surgeon and gastroenterologist Georg Kelling connected an oral insufflation device to a trocar and the Nitze cystoscope to visualise the peritoneal cavity in a dog and thereby became the first known pioneer of laparoscopic surgery [76]. In 1910 Hans Christian Jacobaeus reported the first laparoscopic operation in a human. With the advent of safe methods of establishing pneumoperitoneum and modern advances in endoscopic light sources from the distal electric bulb, the external light unit and sophisticated light-conducting fibreglass bundles together with computer chip television cameras, laparoscopic surgery has become very safe and the gold standard of many operative interventions [77].

The usual modern operative set-up in laparoscopic surgery involves the use of either a rod lens video camera or a digital laparoscope attached to a fibre-optic cable system providing the light source. The laparoscope is inserted through a 5mm or 10mm trocar into the peritoneal cavity to reach the operative field. The peritoneal cavity is usually inflated through the gas connector in the trocar with carbon dioxide to provide the space necessary to operate, typically to a pressure of 14mmHg. The image from the camera is displayed on a two-dimensional monitor within close visibility of the operating surgeon. The laparoscopic approach is now the gold standard for operations such as cholecystectomy and is favoured by many surgeons for procedures such as appendicectomy and splenectomy to colonic resection for malignancy. It is important that surgeons practicing laparoscopic techniques have undergone a clear curriculum and assessment process and there are now national laparoscopic training programmes in the United Kingdom providing some structure to this training [78-80].

2.15.3 Single-Incision Laparoscopic Surgery

Single-incision laparoscopic surgery (SILS) represents a further drive to decrease the invasiveness associated with laparoscopic surgery. It involves operating through a single skin incision, usually placed at the umbilicus. Multiple ports can be placed through this skin incision or one of the specially designed SILS ports may be used [81]. Problems encountered in this technique have been cluttering of instruments and lack of triangulation as they are close together and in parallel. Multiple articulated SILS instruments have emerged to combat these problems and many abdominal operations including appendicectomy, cholecystectomy, splenectomy, colonic resections and bariatric procedures have now been reported in the literature [82]. There is currently a lack of level 1 evidence, however multi-centre randomized controlled trials comparing conventional and single-port laparoscopic cholecystectomy are ongoing. Current evidence comparing single-incision and laparoscopic cholecystectomy suggests no difference in systemic stress (cytokine release) and morbidity between the two techniques [82,83] with potential benefits of improved cosmesis and decreased post-operative pain [84,85]. Disorientation has the potential to be more of a problem in SILS compared to conventional laparoscopic procedures as the angle of view from the camera is likely to be different as it is moved to avoid clashing with instruments at the operative site.

2.15.4 Natural Orifice Translumenal Endoscopic Surgery

The essential concept of Natural Orifice Translumenal Endoscopic Surgery (NOTES) was first described by Wilk in 1994 [86]. The technique involves using a natural orifice such as the stomach, vagina, bladder or colon to access the peritoneal cavity to perform operative interventions rather than using abdominal wall skin incisions. The natural orifice approach offers not only the cosmetic benefit of scarless surgery but also the potential to improve short-term post-operative outcomes. Surgery could be performed without the complications of pain from abdominal incisions, wound infections, hernias, adhesions, and impaired immune function from the surgical stress response. Patients in high-risk groups for conventional surgery could have the greatest benefit from a translumenal approach. In theory NOTES could allow the surgeon to perform some procedures under less than general anaesthesia and outside the settings of an operating theatre. This raises interesting opportunities and has got significant potential implications for healthcare provision in remote areas or in developing countries.

Researchers at Johns Hopkins University published the first report of NOTES transgastric peritoneal exploration for liver biopsy in a pig model, with a series of survival experiments[87]. The same group went on to publish their experience of performing transgastric endoscopic ligation of the fallopian tubes in a porcine model with survival at 2-3 weeks [88]. Wagh et al demonstrated effective systematic endoscopic examination of the peritoneal cavity in a porcine model, with the first successful report of organ resection. They performed NOTES transgastric oophorectomy and partial hysterectomy in 3 animals with uncomplicated 24-hour survival [89]. Subsequent reports of various surgical procedures performed via translumenal endoscopic access in animal experiments include transgastric gastrojejunostomy, cholecystectomy, hepatic wedge resection, appendicectomy, hernia repair, partial hysterectomy and splenectomy in a non-survival model [90-94].

The first step towards NOTES in humans came with reports of transgastric endoscopic pancreatic debridement as early as 2000 [95].The established treatment of choice for uncomplicated pancreatic pseudocysts is transgastric endoscopic drainage, and extending this technique to enable debridement of pancreatic necrosis has had encouraging results in published case reports and retrospective series [96,97]. Marescaux et al performed the first human transvaginal hybrid cholecystectomy using a double-channel flexible gastroscope and standard endoscopic instruments having first obtained pneumoperitoneum using a 2mm transumbilical needle-port [98]. In July 2008, a systematic review reported on 49 human NOTES operations published in the literature, and as of January 2011 there are now well over a thousand published cases of NOTES procedures with several large databases such as the German, EURO-NOTES and NOSCAR registries [99], as well as large multi-centre international trials of both transgastric and transvaginal surgery [100]. The first UK transvaginal hybrid NOTES cholecystectomy was carried out in June 2010 and the operative room set-up is illustrated in Figure 2.6. The vast majority of these cases have been carried out under appropriate conditions at established centres using hybrid laparoscopic techniques, to ensure safety during the assessment of peri-operative outcomes. It is of paramount importance that feasibility studies in NOTES are carried out safely by experienced multi-disciplinary teams in centres with adequate laboratory and in-vivo experience, under an institutional review board-approved protocol as a spike in morbidity and mortality as seen during the introduction of laparoscopic surgery would be unacceptable to both patients and the wider clinical community.

Figure 2.6 Operative room set-up illustrating flexible endoscopic view and labour intensive set-up during the first United Kingdom transvaginal hybrid NOTES cholecystectomy

It is therefore vital in the development of NOTES to continuously reflect on what has been achieved and objectively assess and define the role NOTES may have in the future of MIS. Although reported morbidity of hybrid transvaginal cholecystectomy in the largest series has been acceptable in the region of 3% [99,100], what has become very clear from its introduction into clinical practice is the inadequacy of the flexible endoscope as a NOTES operating platform. There are significant problems with navigation and stabilisation of the flexible endoscope when used outside the constraints of the gastrointestinal lumen. Furthermore, critical operative manoeuvres such as traction and counter-traction for exposure and division of structures are almost impossible using a dual-channel endoscope alone, and there are problems surrounding the sterilisation process of these tools [101]. Another significant flaw in the current flexible access technology is the lack of a reliable enterotomy closure modality, especially in the context of transgastric surgery [102]. Due to the proven safety profile of transvaginal surgery in the context of gynaecological resection, this access route represents a natural first step in the investigation of clinical NOTES. However, as it is only available in half the population and there are concerns around its acceptability in the younger female population [103]. As there are serious concerns regarding sterilization and closure methods in trans-colonic access the transgastric route has emerged as most favourable for research of future clinical applications. Several interesting gastrotomy closure devices have been investigated including the over-the-scope clip system [104] which has some robust experimental evidence supporting its use. Nevertheless, there are issues with the comparability and objectivity of gastrotomy closure assessment methodology as well as the lack of robust clinical evidence to support safe gastrotomy closure. Many surgeons currently feel uncomfortable with the proposed closure techniques and this is probably the most significant reason for the lack of clinical uptake of transgastric applications. With this in mind, what is required is a multi-tasking platform with the ability to enhance operator perception and to perform more complex procedural steps such as suturing and gastrointestinal anastomoses without utilising significant trans-abdominal assistance. Thus far, several operative platforms have been introduced with the aim of solving some of the short-comings of the flexible endoscope. The Olympus R-Scope provides instrument channels at the tip which can be moved at 90 degrees to one another, enabling somewhat more advanced tissue manipulation. The Direct Drive Endoscopic System (Boston Scientific, Natick, MA, USA) allows instrument control through ergonomically driven handles, similar to laparoscopic surgery, and the Cobra (USGI Medical, USA) aims to solve the problem of instrument triangulation through three independent arms at the endoscopic tip. The Spider (Transenterix, NC, USA) allows single access flexible laparoscopy with triangulation of instruments at the tip offering true right and left motion, whilst the Storz video surgical rectoscope (Storz, Tuttlingen, Germany) represents a stable platform for access and resection in trans-anal endoscopic surgery. Unfortunately none of the available platforms available today address all of the requirements necessary to perform complex natural orifice procedures.

Similar to laparoscopic surgery therefore, NOTES will involve the operator using a two-dimensional monitor interface to navigate the peritoneal cavity. However, NOTES in its current form is likely to lead to an increased cognitive load and operator disorientation compared to the laparoscopic approach for a number of reasons. Firstly, the use of the flexible endoscope as an operating platform does not offer the same positional cues of where it is located on the inside of the body as the laparoscope and the instrument itself is much more prone to rotational disorientation on the roll axis, and will provide even less or no haptic feedback. Therefore, to allow for NOTES to be performed by a majority of minimally invasive surgeons in the future rather than a few experts in large research centres, we must ensure that technology is in place to aid the surgeon in perception of the operative environment and decrease the risk of disorientation. Education is likely to play a key role in this aspect, and there is a need for structured higher surgical training programmes for the aspiring NOTES surgeon centred on an objective competency-based curriculum supported by robust evidence as well as technical experience and expertise. The flexible endoscope is a much more difficult instrument to navigate inside the peritoneal cavity rather than within the constraints of the gastrointestinal lumen and is likely to require considerable expertise. The Natural Orifice Surgery Consortium for Assessment and Research (NOSCAR), a joint initiative supported by the American Society for Gastrointestinal Endoscopy (ASGE) and the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES), was set up in July 2005 to oversee and guide through the development and introduction of NOTES into clinical practice [105]. They identified 12 fundamental challenges to the safe introduction of NOTES as illustrated in Table 2.1. Spatial orientation and operator disorientation was highlighted as one of the most important problems which had to be solved prior to the widespread implementation of this technique.

Table 2.1 Fundamental NOTES research challenges as identified by NOSCAR

NOTES Research Challenges
1. Access to peritoneal cavity
2. Gastric (intestinal) closure
3. Prevention of infection
4. Development of suturing device
5. Development of anastomotic (non-suturing) device
6. Spatial orientation
7. Development of a multitasking platform
8. Control of intraperitoneal haemorrhage
9. Management of iatrogenic intraperitoneal complications
10. Physiological untoward events
11. Compression syndromes
12. Training other providers

2.15.5 Perceptual-motor coordination in laparoscopic surgery

When performing laparoscopic surgery, the surgical instruments and camera essentially become extensions of the surgeon's perceptual-motor system. This invariably increases the probability of errors occurring within the system compared with open surgery. Furthermore, this novel arrangement degrades many of the sources of information otherwise available to the surgeon, for instance assessment of relative depth of objects due to the lack of binocular stereopsis, the fulcrum effect of the instruments and change in haptic feedback. Introducing novel visuo-spatial arrangements is likely to further degrade performance.

Holden et al [106] examined perceptual-motor coordination when the configuration of the simulated operation was altered. Changes in the positions of the camera, the surgeon or the objects in the surgical field were manipulated whilst performing a simple laparoscopic transfer task. They found that changes in either the camera or surgeons position disrupted performance however there was no degradation of performance when camera and surgeon positions were changed together. Gallagher et al [107] also investigated the effect of camera rotation on laparoscopic performance and found that visual rotation of the operative field significantly degraded performance and increased error rates of laparoscopic novices in a knot-tying task. Similarly, there was an increase in the time taken to complete the procedure and the error rate of expert laparoscopic surgeons. The result of this experiment were replicated by Conrad et al with manipulation in 15° intervals between 0 and 90° of the camera whilst performing a suturing task [108]. They found that both novice and experienced laparoscopic surgeons showed significant prolongation to completion of suturing tasks with increased errors as the rotational angle increased.

These results suggest that movement of the camera away from the standard view affects performance in laparoscopic tasks, more so for novices than experts. This deviation can obviously be a direct result of user disorientation. Alternatively, it may lead to disorientation which may be responsible for the decrease in performance if not recognised. Furthermore, when disorientation is recognised, the cognitive load of reorientation may impair performance in addition to learning to perform the task in the novel conditions.

2.15.6 Laparoscopic cholecystectomy and disorientation

Laparoscopic cholecystectomy was the first widely adopted application of laparoscopic techniques in general surgery. It is now the gold-standard approach to this operation and remains one of the most commonly performed laparoscopic procedures world-wide. 54,202 cholecystectomies were performed in the UK between April 2006 – March 2007, according to the hospital episode statistics (HES) database. One of the most important complications of this operation is major bile duct injury, which is associated with a mortality of 3% [109], a complication rate of 26% [110] and significant associated morbidity and healthcare costs. The rate of major bile duct injury has remained in the range of 0.3 -0.5%, with most injuries going unrecognised at the time of surgery, although a recent study from Holland has reported rates of up to 1% [111]. It is known that the major cause of bile duct injury is misidentification of the biliary anatomy, and because 3 out of 4 injuries are not recognised intra-operatively it has been suggested that traditional surgical teaching provides inadequate reference points to prevent duct misidentification and that the most significant factor is spatial disorientation on the part of the surgeon [112]. Mistaking a small common bile duct for a cystic duct is the most common cause of injury. Spatial disorientation could lead to a surgeon dissecting on the medial side of the common bile duct, mistakenly believing that the cystic duct is being displayed. Hugh suggests new operative strategies drawn on training in "high-reliability organisations" within the aviation and maritime industries, including navigation-based principles, a system approach and teaching of human factors in error prevention for further reduction in bile duct injuries during laparoscopic cholecystectomy [112].

Dekker and Hugh [113] proposed that the rate of bile duct injury is unacceptably high even in the hands of expert surgeons, and therefore a systemic predisposition to the injury is intrinsic to the operation. They analysed the psychology and heuristics of surgical decision-making in relation to duct misidentification. They concluded that underestimation of risk, cue ambiguity and visual misperception were important factors in this process, and suggested that training of surgeons should emphasise the need to be alert for cues that the incorrect duct is being dissected and that bile duct injury might have occurred.

It is impossible to calculate the proportion of bile duct injuries resulting from operator spatial disorientation since this is very difficult to quantify retrospectively. The operator may not even have been aware he was disorientated, or may have been mistaken in the reorientation process, however it is likely to account for substantial proportion of this type of surgical complication.

2.16 Human error, minimally invasive surgery and parallels with the aviation industry

There has been considerable work within the academic surgical community over the past decade to improve our understanding of human error in order to decrease its impact in the operating theatre [114-116]. It has been estimated that human error occurs in 5-15% of hospital admissions worldwide [117], and that in the UK health system alone an estimated 840 deaths per annum are directly attributable to human error [118]. The operating theatre is clearly one of the most high risk environments for the occurrence of human error with significant consequences, due to the complex nature of technology, personnel and procedures taking place. In the previous section it has been illustrated how operator disorientation can be the cause of human error and patient morbidity and mortality in the specific context of a laparoscopic cholecystectomy. It is intuitive that disorientation therefore can represent the main causative factor of error during an operation, and has potential to jeopardize patient safety in multiple other individual scenarios and operations. However, to fully understand disorientation in the context of human error in the operating room it is helpful to draw comparisons with ideology and research on human error from the aviation industry. It is estimated that over 70% of aviation accidents occur due to human rather than technical error [118] and as such the aviation industry has allocated significant resources to education, systems and procedures in identification, prevention and minimisation of error by pilots [119]. This high resource allocation throughout the last 50 years has resulted in the excellent safety record enjoyed by the modern commercial airlines. Although there are considerable differences between MIS and aviation, it is obvious that aviation as well as other high risk industries such as Formula One, nuclear power and the military are significantly more advanced in both their understanding and evaluation of disorientation as a facet of human error.

In the human factors aviation psychology literature, there exist a number of theories or perspectives on human error. Each of these is characterized by some assumptions about the nature of the error itself as well as its underlying causes [120]. Many of these error models are directly applicable to MIS and provide logical frameworks in which disorientation can be placed in the context of human error. The most relevant error perspectives are described below:

2.16.1 Cognitive perspective

This perspective recognises that there are several stages or mental operations that mediate between stimulus input and execution of response. If one or more of these mediating operations fail to process information correctly, an error can occur. Rasmussen developed a taxonomic algorithm for classifying various types of information processing failures associated with the execution of an erroneous action [121]. The algorithm includes stimulus detection, system diagnosis, goal setting, strategy selection, procedure adoption and action stages. This is adapted within the context of MIS in Figure 2.7, and stages prone to error due to operator disorientation are highlighted. As can be seen if the operator is not orientated all error except for structural or mechanical errors may occur.

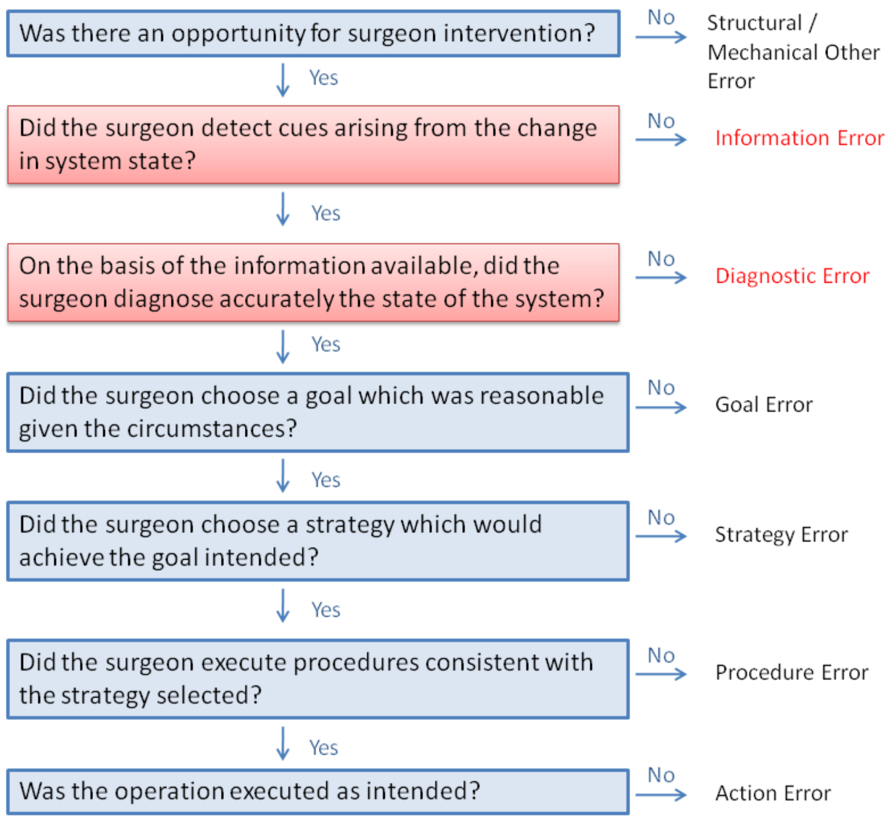


Figure 2.7 Taxonomic algorithm for classifying information processing failures adapted for MIS. Stages highlighted in red indicate where the system is most prone to failure due to operator disorientation and ensuing errors.

Analysis of large databases of aviation accidents using this algorithm have concluded that judgement errors were associated with major accidents, whereas procedural and response execution errors were more likely to occur in minor accidents. Errors due disorientation clearly affect the former and were associated with more serious outcomes.

2.16.2 Ergonomics and system design perspective

This perspective hypothesizes that the human is rarely or never the sole cause of an error. It states that "system models recognize the inseparable tie between individuals, their tools and machines, and their general work environment" [122]. The SHEL model as proposed by Edwards [123] is illustrated in Figure 2.8 below:

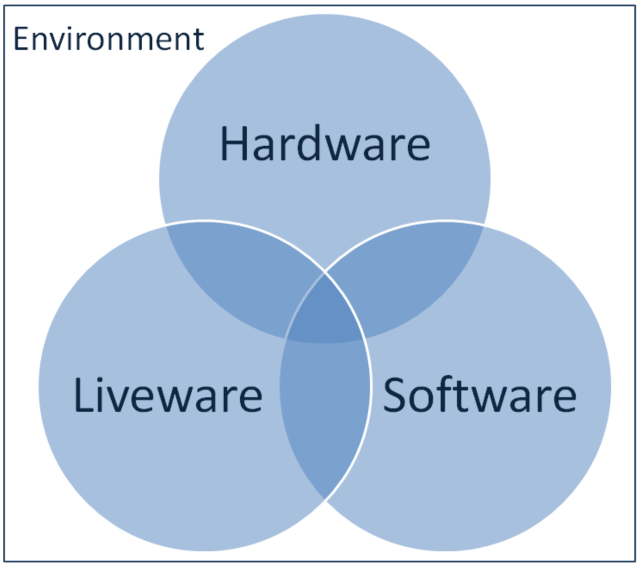


Figure 2.8 The SHEL model of system design illustrating interaction between hardware, software, liveware (the human) and the environment.

This model describes four basic components and system failures are said to occur when there is a mismatch between these components, when other environmental or task-related stressors degrade operator performance. Operator disorientation is clearly a significant factor which can lead to break-down and error at any point and within the majority of interactions in this system as the human-machine interface is critically important during MIS procedures. Errors can therefore be analyzed in a meaningful way that will identify possible mismatches between mechatronic requirement and operator characteristics.

2.16.3 Aeromedical perspective

This approach suggests that errors are often caused by some underlying physiological condition of the operator. In aviation this refers to hypoxia, dehydration, fatigue or spatial disorientation of the aircrew [120]. These conditions in turn can be caused by a number of other factors such as illness or fatigue. This perspective states that these physiological conditions should be seen as pathogens that exist insidiously within the individual until they are triggered by environmental conditions and manifest as errors. The implication of this for surgery is that if a surgeon is not physiologically fit or optimised then all other systems including those defined in the SHEL model will be negatively affected. They therefore suggest that the most important factor in preventing error is the physiological status of the operator. In MIS it is clear how disorientation is one of the most significant factors which can affect the "physiology" of the surgeon and the entire system leading to errors.

2.16.4 Psychosocial and Organizational perspectives

The psychosocial perspective suggests that the systems should be viewed as social interactions between various agents. It is clear how disorientation of any member of the cohort interaction can have a detrimental effect on the system. In the organizational perspective theories such as the "Swiss Cheese" model [124] suggest that several levels of human failure have to exist simultaneously, with each one influencing the next, in the majority of significant errors.

2.17 Conclusion

Disorientation is a phenomenon which has been widely studied in aviation and virtual world industries and has a long history of research within the psychology community. There is a distinct lack of data in relation to surgery however we know that it is associated with serious complications, morbidity and mortality. Our lack of understanding is likely to be due to the relatively short period of time since the widespread introduction of MIS and the increased association of this with operator disorientation compared to conventional open surgery. It is clear from simply studying the operation of laparoscopic cholecystectomy that surgeon disorientation is associated with significant patient morbidity. With the introduction of further minimally invasive techniques, such as NOTES, operator disorientation will pose an even greater problem with current technologies. Figure 2.9 summarises the processes and factors surrounding orientation in NOTES and provides some ideas about reversing and aiding these processes:

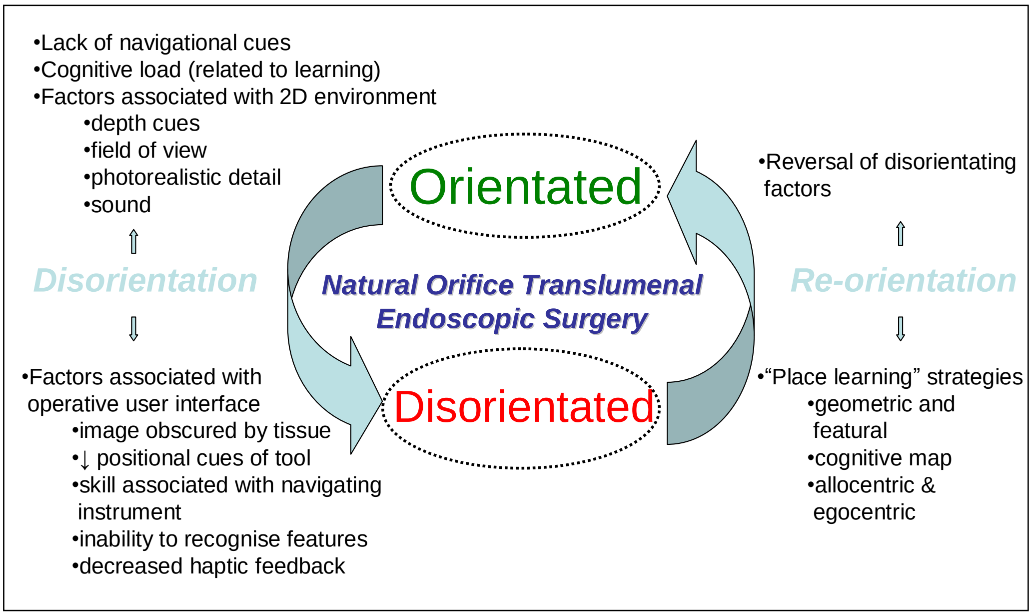


Figure 2.9 The cycle of orientation and relevant factors outlined in Chapter 2

The important studies and innovations within aviation, virtual worlds and fields of psychology described in this chapter provide us with valuable information and ideas as to how this research can be applied to find solutions to the surgical disorientation paradigm. Currently there is very limited understanding of perception and orientation as a whole in relation to MIS. The key to understanding orientation is likely to lie in the ability to objectively quantify the psychophysical phenomenon and the factors that influence it. To this end, eye tracking technologies can provide us with information on the visual search and inferred attention behaviour associated with the processes surrounding orientation under the correct experimental conditions. As the visual system is responsible for the vast majority of sensory input during orientation the eye tracking signal should hold the key to understanding behavioural patterns and characteristics. By studying temporal changes of this signal it is theoretically possible to develop a framework by which differences in behaviour can be profiled, described and quantified at a collective and individual level.

Chapter 3 A hidden Markov model-based analysis framework using eye-tracking data to characterise orientation strategies in minimally invasive surgery

This chapter is based on a study published in Cognitive Processing and presented at the International Conference of Spatial Cognition, Rome, 14 – 19 September 2009 as referenced in introductory chapter.

3.1 Introduction

In Chapter 2, some of the difficulties encountered in navigation using an endoscope in intra- or extra-lumenal surgical procedures were summarised. One of the main reasons discussed was operator disorientation. As outlined in the previous chapter operator disorientation can result from a number of factors including lack of navigational cues, increased cognitive load on the operator, a restricted field-of-view of the operating endoscope resulting in decreased operator awareness of surroundings and the endoscope location in space, as well as when the endoscope is navigated too close to surrounding tissue, resulting in the whole display screen being reduced to one colour or texture. It is important to prevent operator disorientation in endoscopic procedures; however, it is equally important to efficiently and correctly orientate when in a disorientated state, to ensure safety for the patient and decrease likelihood of a surgical error. It is likely that as endoscopic procedures are carried out extralumenally in larger spatial environments than the gastrointestinal tract, such as in NOTES, disorientation will represent more of a problem, imposing greater emphasis either on the abilities of the operator to orientate efficiently or on technology to provide solutions to the increased perceptual problems.

Although eye-tracking technology has been used extensively to characterise basic eye movement behaviour when subjects are disorientated in the aviation industry [37], the experiment described in this chapter represents the first attempt to analyse visual orientation strategies in the context of surgery or any other medical field. In this chapter, we aim to analyse the particular characteristics of sequences of fixations in an attempt to quantify orientation behaviour. Previously described methods for analysing and comparing fixation sequences generated by eye-tracking data include obtaining feature space fixation density functions that are normalised to the image content along the scan paths [125] and analysis frameworks based on earth mover's distance (EMD) in normalised anatomical space [126]. These methods focused on unveiling the visual features of the fixation sequence or scan path, rather than on exploring behavioural similarities. We explore similarity-based Markov models as a novel alternative to profile these behavioural patterns. Although Markovian modelling of fixation sequences as represented by fixated region of interest has been previously introduced [127], a direct comparison of fixation sequences of different length was obtained by the so called string editing measures, which involves arbitrary manipulation of the sequence. The solution proposed here capitalises on the transformation of the problem of comparing sequences to a more tractable problem of comparing patterns.

The hypothesis to be tested in this chapter is that when humans are disorientated there exist discrete patterns in psychophysical visual behaviour used to orientate in this simulated environment. These patterns can be quantified and described and may be associated with performance in orientation. The potential advantage of using and validating this analysis framework is the ability to understand the attention distribution of the temporal eye tracking signal in a more meaningful way. It could potentially allow us to study individual gaze behaviour and relate that to more generalised cohort behavioural patterns and potentially link this with other outcome parameters such as task performance. Should this be the case then it would seem plausible that these strategies may be utilised in an educational setting to allow operators to orientate more effectively during MIS thereby critically minimising danger to the patient should the operator becomes disorientated. In the future, further applications may involve using this information to allow a robotic human-computer interface to recognise disorientation in an operator [128].

3.2 Methods

3.2.1 Subjects

18 subjects were recruited to participate in the study. 3 of these were excluded due to inadequate data collected from the eye-tracker (>50% total missing data). The remaining 15 subjects (14M: 1F) with a mean age of 29.3 years (range 20 – 48 years) were considered for analysis. 7 of the subjects were doctors with varying degrees of endoscopy experience (5 surgeons and 2 endoscopists). The other subjects were a mixture of engineers, medical students and postgraduate researchers.

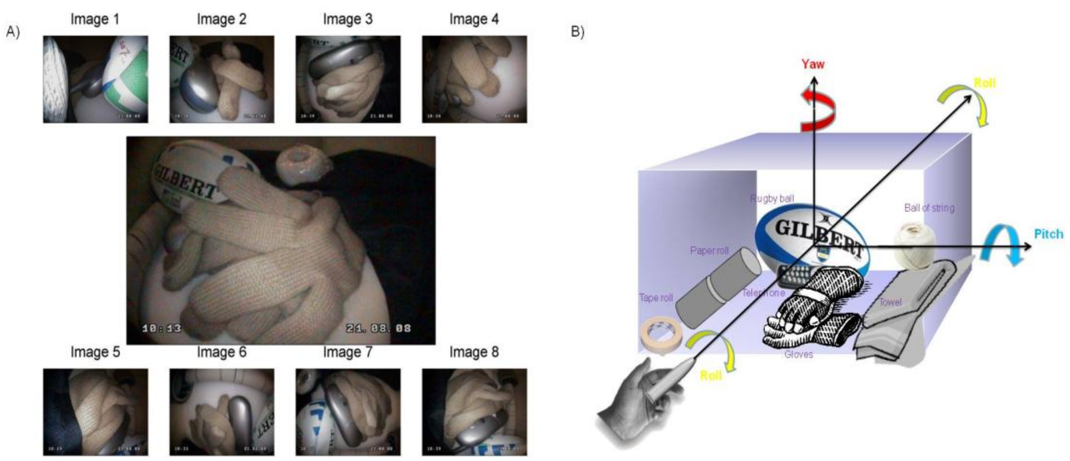


Figure 3.1 A) Original image (centre) and subsequent images seen by subjects. See table 3.3 for ground truth rotations of images. B) Schematic diagram shown to subject prior to experiment with depiction of the reference system for pitch, yaw and roll movements illustrated with respect to the centre of the box

3.2.2 Experimental design

Subjects were shown a reference colour photograph of everyday objects placed in a box trainer as illustrated in Figure 3.1. The objects were chosen and arranged as to resemble the approximate sizes, proportions and shapes of organs in the peritoneal cavity. This representation was used to reduce any disadvantage conferred on subjects without human anatomical knowledge, or varying experience of anatomy and endoscopy. Subjects were additionally shown a colour schematic diagram of the box with labelled contents represented as illustrated in Figure 3.1 prior to the start of the experiment so that they could familiarise themselves with the spatial and non-spatial features of the objects. The pictures were taken using a single channel gastroscope camera (Model 13907PKS, Karl Storz GmbH & Co, Tuttlingen, Germany) in order to replicate the same quality of picture seen in endoscopic surgery. Subjects were told that this was the correct orientation of the camera and they were subsequently presented with a different image. The new image was of the same scene however the camera had moved in three possible directions; yaw, pitch and roll with respect to the boundaries of the box trainer. The view could move either in one or a combination of these directions (See Figure 3.1). This is of particular relevance to disorientation in NOTES since in laparoscopic surgery the extra-corporeal position of the camera is indicative of the yaw direction, making disorientation in this direction unlikely. The subjects were asked to describe how the camera had moved from the original picture with respect to the boundaries of the box and were told the answers were all in increments of 45° from the original image in any direction. There was no time limit and the entire field-of-view of the cardboard box was not visible in all pictures. When subjects were satisfied with their answer they conveyed this to the investigator who showed them the original image again. At this time subjects were requested to record their answers of the three possible image manipulations (yaw, pitch & roll) on an answer sheet to ensure collection of eye tracking data during reorientation was not affected. By recording the answers as a change in one or any of the directions described in increments of 45° from 0-360° answers were able to be scored in a binary fashion. When subjects were ready, they were presented with the next image where the camera had moved. This process was repeated for a total of 8 different image stimuli. Subjects were always shown the original image in between and were not told if their answers were correct or incorrect.

3.2.3 Eye-tracking

Gaze tracking was performed using a Tobii ET 1750 eye tracker (Tobii Inc, Sweden). This is an infrared video-based binocular eye-tracking system recording the position of gaze in the work plane (screen) at 30 Hz. Infra-red light source is beamed towards the eye whilst a camera records the position of the reflection (known as the Purkinje reflection) on the cornea surface relative to the pupil centre. The infra-red signals are real-time digitized and processed. Following a calibration procedure, the point of regard can then be determined with an accuracy of 1 degree across the work plane. This allows accurate tracking of the position of gaze of subjects standing approximately 60cm away from the equipment looking at the monitor. Fixations were detected using the dwell time algorithm by which a fixation is considered if the gaze does not move more than a hard threshold, 30 pixels in this case, during a minimum of a 100ms. These are common parameters for fixation identification.

3.2.4 Outcome measures

The outcome parameters of this study were time taken to provide each answer as indicated by the time used to study each image, whether the answer was correct / incorrect, basic eye-tracking parameters such as fixations, dwell-time, and number and length of saccades. Other outcome parameters were fixations on regions of interest (ROI) as determined by objects occupied in the scene and order in which objects were fixated upon. Each image or stimulus was manually segmented into ROIs delimiting the different objects, and each object representing ROI maybe composed of several polygons or subregions. The list of objects representing ROIs were standardized for all stimuli, i.e. the same list of objects were declared for all images, although their attached image subregions differ across images. When an object was not visible from a certain angle, its ROI simply has no attached polygons. Table 3.1 displays the ROIs featured in each image.

Table 3.1 Regions of interest featured in each image

Image	1	2	3	4	5	6	7	8
Region of interest								
Background	x	x	x	x	x	x	x	x
Ball	x	x	x	x	x	x	x	x
Glove	x	x	x	x	x	x	x	x
Phone	x	x	x	x	x	x	x	x
Ball of string	x	x		x			x	
Black towel	x	x	x	x	x	x	x	x
Writing on ball	x	x	x	x	x	x	x	x
Green on ball	x	x	x				x	x
Blue on ball	x		x		x		x	x
Light reflection on phone	x		x	x	x		x	x
Number on phone			x				x	x
Paper roll			x	x	x	x	x	x
Tape roll			x	x	x	x	x	x

3.2.5 Statistics

Comparisons between groups of non parametric variables were done using the Kruskal Wallis test with individual variables compared using the Mann Whitney U test as necessary. All analyses were performed using statistical software (SPSS v16.0, Chicago, USA). Differences were considered statistically significant at $p<0.05$.

3.2.6 Similarity-based visual behaviour profiling using HMM

As the participants are shown each new image stimulus to discern its orientation, theirs eye-gaze navigates between the objects in the scene exposing differences in visual behaviour. We analyse these differences in visual behaviour using a similarity-based profiling algorithm using Hidden Markov Models (HMM) [129,130]. This method has already been used for behaviour profiling [131] however it has never been validated in the context of eye tracking or orientation.

Accepting that fixation locations embody visual attention, the temporal sequence of fixations is likely to contain information regarding the orientation strategy of the observer. Therefore, the basic idea is to represent visual behaviour as captured by a fixation sequence as a point in a plane or 2D plot. The positions of the different visual behaviour patterns within that output plane is determined by a relation of similarity among the patterns / temporal sequences of fixations, with patterns representing similar behaviours projecting to close locations in the plane. Critically, coordinates in the chart of the point symbolising the fixation sequence are generated in such a way so that the point spatial location reflects its similarity with other fixation sequence points that are nearby and dissimilarity with those far away. With such representation it becomes possible to characterise prototypal orientation strategies shared by a number of observers. Moreover, by labelling the points associated with certain behavioural patterns or outcomes it is also possible to identify advantageous schemes.

Discrete HMMs are finite state stochastic machines similar to Markov chains but in which the state are not directly observable [132]. An HMM can be represented as $\lambda(A,B,\pi,S)$ where A represents the transition matrix among hidden states, B represents the emission matrix, π represents the initial state distribution and S represents the alphabet of observable symbols. The parameters of the HMM may be learned using the classic Baum-Welch algorithm [133]. A sequence representing the visual behaviour was then built for each participant and each stimulus based on the ROI gazed at each fixation. Fixation based sequences were then constructed in two fashions:

- Type 1: Each fixation represents a time point in the sequence, and the corresponding ROIs were used as the observed symbol.
- Type 2: Fixations are split into smaller subfixations of 100ms, and each subfixation becomes the basic time point. The corresponding ROI for the subfixation was used as the observed symbol.

Sequencing under the type 1 will put more emphasis on the relevance of the sequence of objects for orientation regardless of the dwell time spent on them, whereas the sequence of type 2 will emphasize the dwell time spent on each object. Because the object representing ROIs have been standardized the alphabet of observable symbols is shared across all stimuli.

The visual behaviour profiling algorithm is based on that of Bicego et al [129,130] for clustering and classifying sequences.

1. Construct the set of observed sequences O of ROIs according to the fixations.
2. Train one HMM $\lambda_i(A,B,\pi,S)$ for each sequence O_i.
3. Compute a distance matrix $D=\{d_{ij}\}$ where $d_{ij}=d_{ij}(O_i,O_j)=\log P(O_i \mid \lambda_j)$. Matrix D represents the non-symmetric similarity between sequences.
4. Using the whole set of sequences as references ($R=O$), build a new representation space H, where each sequence O_i is represented by a vector of features $H_R(O_i)$.

$$H_R(O_i)=\frac{1}{L_i}\begin{bmatrix} d_{i1} \\ \vdots \\ d_{ir} \end{bmatrix} \qquad (1)$$

where L_i is the length of the sequence O_i. The new representation yielded by the last step, transforms a problem of matching sequences, to a more tractable domain of matching patterns. This new representation however suffers from the well known curse of dimensionality [134]. Therefore a last step achieving a reduction of dimensionality is necessary before profiles can be described.

5. Compute a symmetric matrix of pairwise distances among pattern represented sequences in H using the Euclidean distances between patterns $H_R(O_i)$, and reduce dimensionality using the classical multidimensional scaling.

The classic k-means algorithm [134] was used to compute the centroids of the groups of interest; in brief this is a method of cluster analysis where each observation is partitioned into a cluster with the nearest mean, with the centroid being closest to the mean.

3.3 Results

There was no difference in performance between medically trained subjects and non-medically trained subjects (p=0.86). Furthermore there was no difference in performance between endoscopists (n=2) and surgeon (n=5) subjects (p=0.865). Overall subject performance was divided up into 3 groups as follows: low performance (0-2 correct answers, n=3), medium performance (3-5 correct answers, n=7), and high performance (6-8 correct answers, n=5). Analysis aimed to answer the 3 questions posed below:

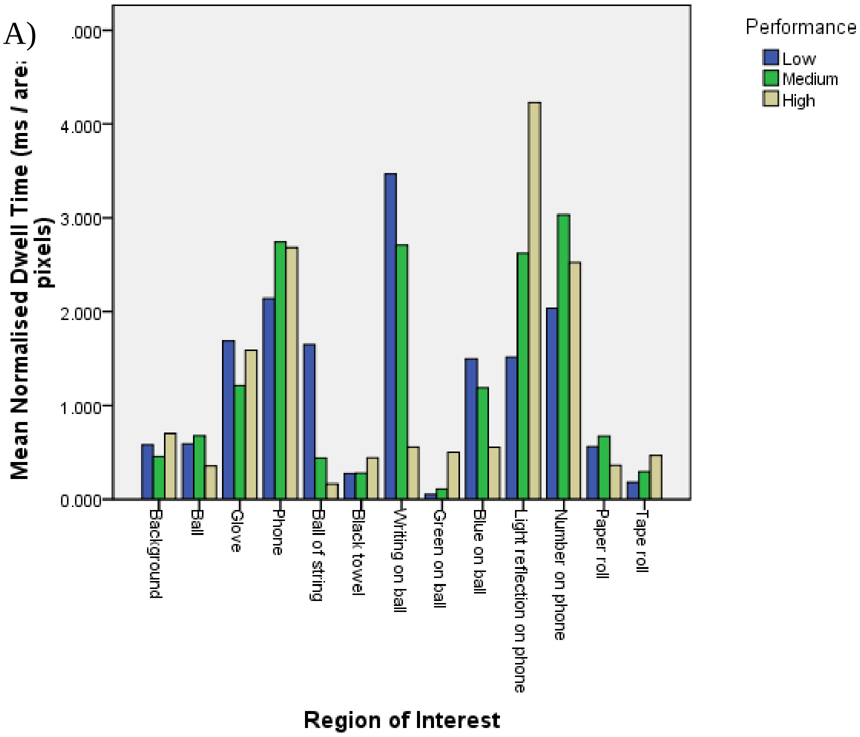
3.3.1 What are particular features focused on by each group?

Basic eye tracker parameters are compared between performance groups in Table 3.2. As can be seen the high performance group utilise less fixations, a greater mean cumulative length of saccades and less normalized dwell time per region of interest. This indicates that overall these subjects used a more structured approach with clear targets and strategies to obtain the information necessary for orientation. Dwell times were normalised per individual subject picture by dividing the absolute dwell time by the percentage of area occupied by that region of interest within the image. Overall normalised dwell times for each region of interest of the performance groups are illustrated in Figure 3.2a. There were some notable differences between subject groups when examining the normalised dwell time per region of interest. Subjects who performed with greater performance index had a higher normalised dwell time than those who performed lower on the phone (2.682 v 2.139 ms/pixel^2), the light reflection on the phone (4.229 v 1.514 ms/pixel^2), and the number on the phone (2.521 v 2.036 ms/pixel^2). This represents the central region of interest in all images. The low performance group had a statistically significant higher normalised dwell time compared to the high performance group on the peripheral regions of interest of the ball (0.591 v 0.353 ms/pixel^2), writing on the ball (3.467 v 0.555 ms/pixel^2), and paper roll (0.559 v 0.360 ms/pixel^2) and also spent a higher amount of normalised dwell time on the blue on the ball (1.495 v 0.553 ms/pixel^2) and the ball of string (1.647 v 0.164 ms/pixel^2). Figure 3.2b illustrates the normalised dwell time per ROI taking into account the answer given per image. As expected this shows a very similar trend as when separated into performance groups.

Table 3.2 Comparison of overall basic eye tracker parameters

	Low performance group	Medium performance group	High performance group	P
Mean time taken to answer (sec)	21.5	18.7	21.7	0.842
Mean / median number of fixations	44.1 / 32	41.1 / 34	24.2 / 19	<0.001
Mean fixation duration (ms)	0.401	0.33	0.333	<0.001
Mean / median number of saccades	28.4 / 25	34.6 / 31.5	35 / 30	0.54
Mean cumulative length of saccades	7842.5	18017.7	27134.3	<0.001
Mean absolute dwell time / ROI (ms)	1284.5	932.5	555.4	<0.001
Mean normalised dwell time (ms/pixels^2)	1.248	1.264	1.163	0.002
Missing data (%)	7.56	6.7	7.43	0.109

A)



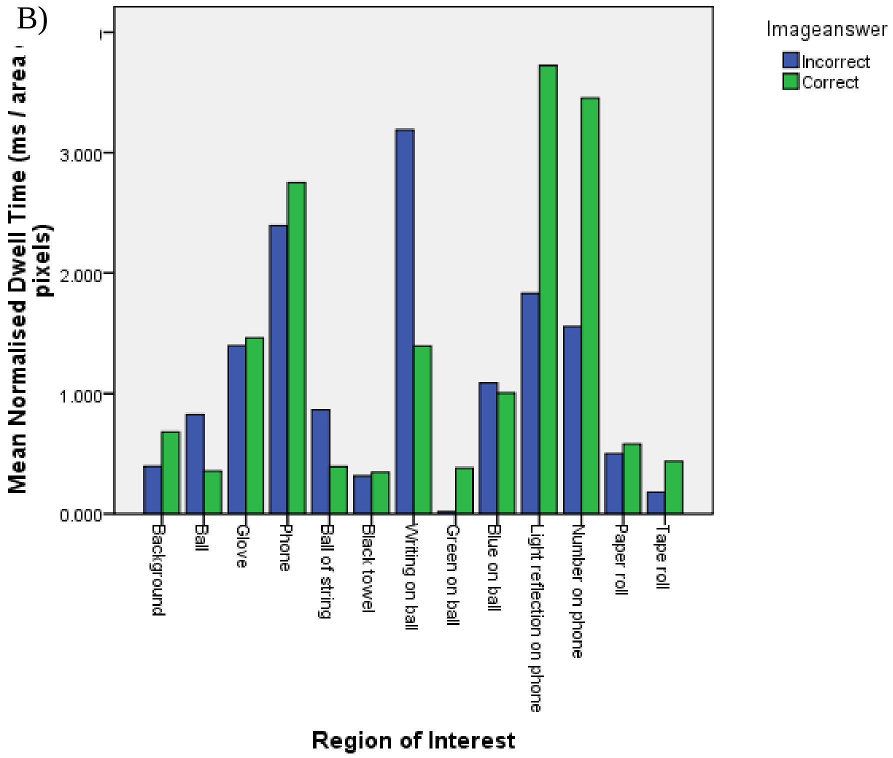


Figure 3.2 Overall normalised dwell times per ROI across all images. A) The three bar series represent groups of varying overall performance, and B) the two bar series illustrates the different gaze distribution depending on whether the participant answered correctly or not

As mentioned previously, shorter normalised dwell times by the high performance group on most objects apart from the central one and greater cumulative length of saccades may suggest a structured approach to orientation, scanning a larger area but dwelling less on each ROI whilst focusing heavily on position and orientation of the central object. This may be interpreted as suggestive of scanning behaviour of the position of the peripheral objects relative to the central one and therefore a discrete reorientation strategy; however these data will be examined in more detail to objectively confirm this in the temporal analysis of fixation distributions. It is apparent however that focusing heavily on peripheral objects such as the ball and in particular the writing on the ball by the low performance group was not a successful reorientation strategy.

3.3.2 What manipulations of the image prove the most difficult to re-orientate from?

It is evident from Table 3.3 that 90° roll or yaw manipulations were equally difficult to re-orientate from. Furthermore, when seen in combination even fewer subjects answered correctly. The most difficult combination appears to be a combination of all 3 manipulations as illustrated in image 8. Since these movements are non-commutative it is possible for images with 2 or more manipulations in different directions to have more than one answer in terms of combination of manipulations used to go from the original image to each experiment image. All subject answers were examined for this and all subjects who answered correctly stated the same combination of image manipulations as answers. This may be because the manipulations described in Table 3 correspond to the simplest and most direct route from the original image to the next and this showed similarity of mental imagery between subjects who answered correctly. Mental imagery has been described as the ability to mentally represent the information available within the environment. In the psychology literature it has been reported that there is a relationship between an individuals' topographical orientation skills and mental imagery abilities. It was suggested that the ability to form a cognitive map of the environment is significantly correlated with the ability to perform mental rotations of simple geometric shapes [135]. This is clearly a factor that can contribute to performance in this experimental set-up and which was not explored, however the relative homogeneity of correct answers in the way subjects described the same 3 directions to reach the new image suggests a similar cognitive map in high performance subjects, which supports this hypothesis.

Table 3.3 Orientation of images with performance of subjects in each image

Image	Yaw	Pitch	Roll	Correct	Incorrect
1	180°	0°	0°	9	6
2	90°	0°	0°	8	7
3	0°	90°	0°	14	1
4	0°	0°	90°	8	7
5	90°	0°	90°	6	9
6	0°	90°	90°	9	6
7	0°	90°	90°	11	4
8	90°	45°	90°	4	11

3.3.3 Are there differences in the sequence of fixations deployed by different subject groups?

After analysis of all the output graphs of the visual behaviour profiling, it was apparent in some cases that there were groups of points that were related by performance of subjects; however this did not appear to be uniform. In the images where this was the case, it indicates similarity of behaviour and is most striking in images 3 and 4 which are illustrated in Figures 3.3 and 3.4 respectively. It is however apparent that subjects cluster very clearly with similarities in visual behaviour as illustrated by the relevant gaze plots in Figures 3.3 and 3.4, thereby providing validation of using this method in profiling visual attention behaviour.

In Figure 3.3, it can be seen that high performance subjects (blue circles) are grouped together on the left of the graph, and when inspecting the gaze plots in this cluster such as subjects 10, a specific reorientation strategy can be described. The choice of anchor object was very clearly the glove in this image and once this ROI was identified peripheral ROIs were identified and directly related to the position of the glove via subsequent fixations. The peripheral ROIs used in this strategy in order of fixations were phone, paper roll, tape roll and black towel. Low performance subjects 1, 16 and 17 (gaze plot for subject 1 illustrated in Figure 3.3a) however show very distinct behaviour, focusing mostly on the phone whilst subject 8 who appears separate from all other subjects has focused mainly on the phone and subsequently the paper roll to deduce orientation as seen in Figure 3.3c. Based on this graph it can be seen that the first component describes the anchor object which in this case is the central object of either glove or phone with the middle of the abscissa axis representing a mix of attention between the two main anchor objects (as illustrated in Figure 3.3b). This example also illustrates that in this particular case, which is a pitch only manipulation of the image, it does not matter what anchor object is used as subjects were likely to get the right answer whichever one they chose (see Table 3.3).

In Figure 3.4, there appears to be convergence of all subjects who orientated correctly to the left of the graph and all who answered incorrectly to the right. When looking at the gaze plots, a shift to the right on the abscissa axis in this graph represents a distinct focus of attention on the glove as illustrated by subjects 16 and 17 and a shift to the left represents increased focus on the phone as illustrated by subjects 2 and 7, confirming that the first component of the output graph represents the anchor object. However, the solution may be flipped due to the ill-posed nature of the problem. This example illustrates well how when subjects are faced with a difficult orientation task such as roll (see Table 3.3), the selection of the anchor point is critical as all subjects to the right in this graph answered incorrectly, which corresponds to choosing the glove as the main anchor point. Subject 7 lies closest to the point of centre of gravity of subjects who answered correctly. When examining the gaze plot of this subject in Figure 3.4a a distinct successful reorientation strategy can be deduced. It appears that this subject chose the phone as the anchor object with initial fixations identifying this ROI. Following that several ROIs were identified in turn and each time related back to the position of the anchor object via subsequent fixations. These ROIs were background, glove, ball and black towel and following each fixation on one of these peripheral ROIs the anchor object was fixated upon to deduce its relative relation and therefore overall orientation. Subjects 8 and 4 are positioned peripherally because they appeared to focus more on the toilet roll and background respectively than the others on this side of the graph.

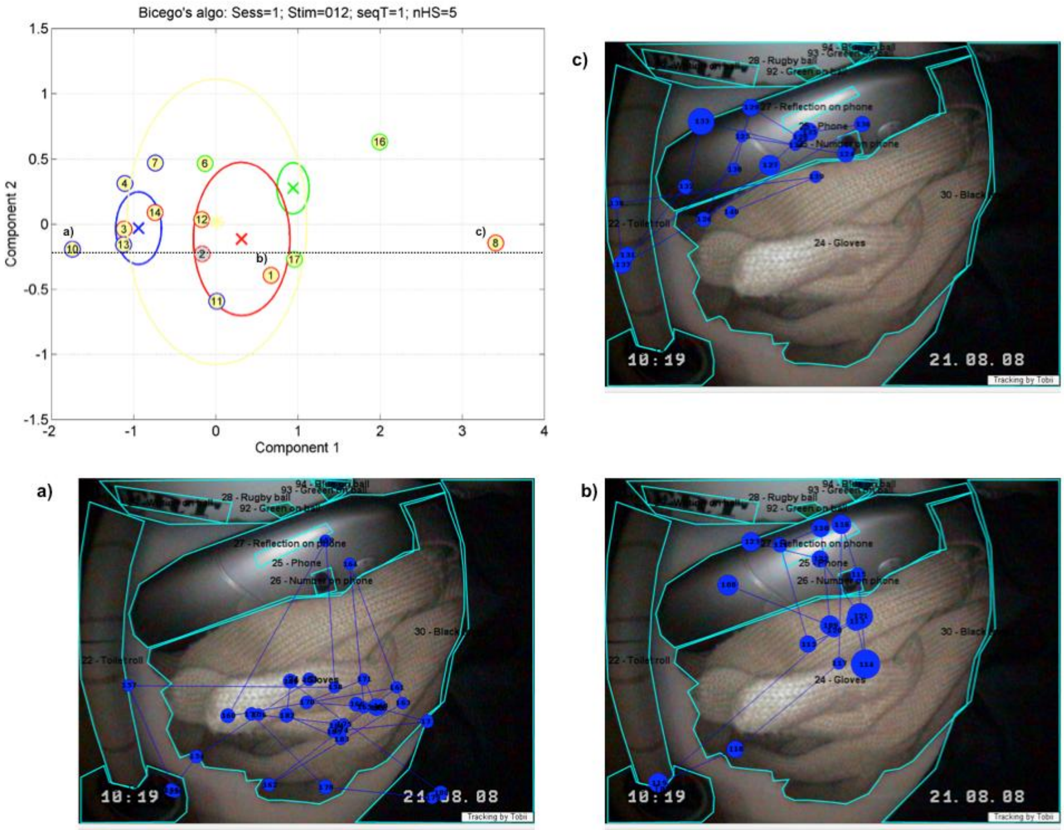


Figure 3.3 Example of visual path profiling algorithm output illustrating subject performance (blue=high, red=medium, green=low) and answer, (grey shading=incorrect answer, yellow shading=correct answer) for fixation sequence of Type 1 under the stimulus image 3. Subject numbers are represented within circles. Groups centroids are illustrated by colour coded crosses, with the average distance of each group to its group centroid is represented by the surrounding circle. Letter figures represent the particular gaze plots of the marked individual subjects with each consecutively numbered point representing dwell time of that particular fixation. Importantly, this figure highlights the relation between the first component of the embedding and the chosen reference anchor object. Selected subjects lie along a line parallel to the main component axis to minimise the effect of the second component.

The strategy used by those who performed well appeared to be that of choosing an anchor object, which for most of the images was the phone (i.e. the most central object), and related the position of some peripheral objects to this one to determine the manipulation of the image. In some image manipulations such as in Figure 3.3 high performers appeared to change their anchor object to the glove. Subjects who performed poorly appeared to adopt a more random re-orientation strategy.

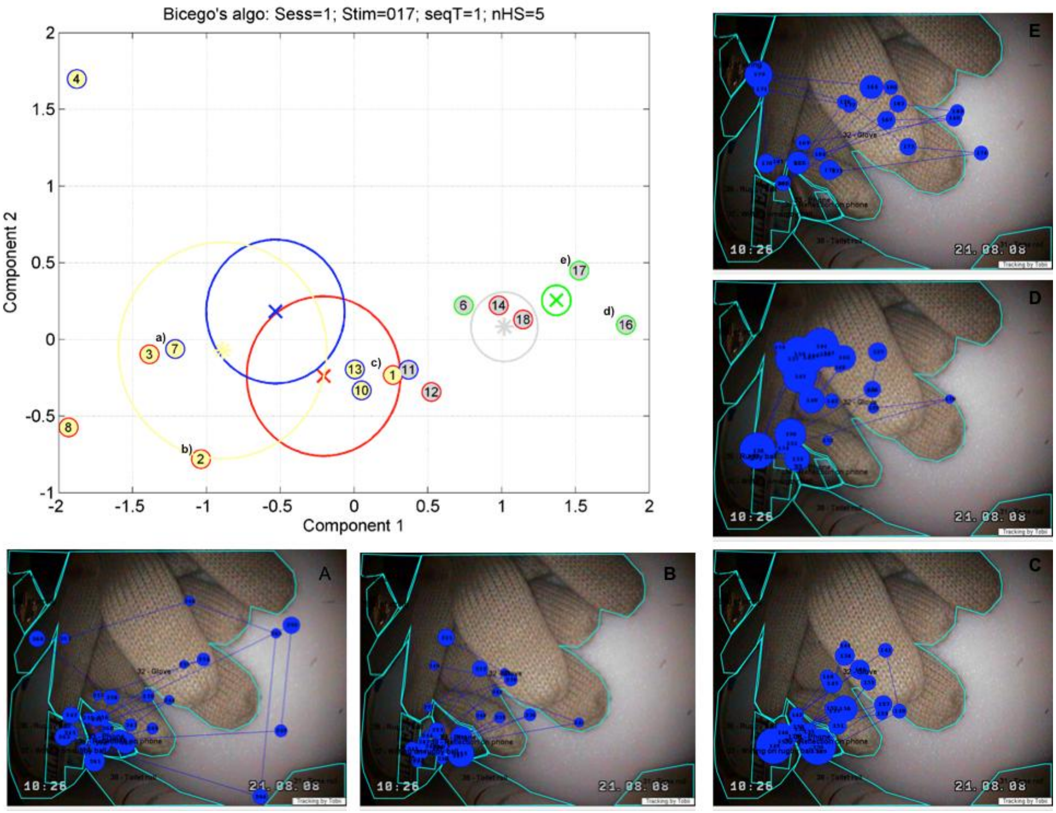


Figure 3.4 An example of the visual path profiling algorithm illustrating the importance of orientation strategy to successful outcome. Colour coding as in Figure 3.3

3.4 Conclusion

There are discrete psychophysical behavioural patterns associated with effective orientation. These patterns have been unveiled for a simulator model based on everyday objects using a profiling method based on the sequence of fixations on the scene recorded by eye tracking. High performance behaviour appears to involve a strategy whereby subjects orientate by determining relative positions of peripheral objects to a central one, on which a significant amount of attention is spent. This strategy suggests integration of both geometric and featural information in a systematic way and using the newly presented egocentric position of a dedicated reference object in relation to the subjects' memory of its allocentric position of the object in the reference image. Using selective featural cues for orientation in this model was associated with less effective performance. The results of this study support data in the psychology literature that humans use relations among stimuli for successful reorientation, or place learning[70]. As previously described in Chapter 2 [59] geometric search strategies are universally employed and developed from birth thereby operating on a sub-conscious level, however this experiment suggests that individuals employ a range of different strategies, geometric, featural and a combination of both, contributing to degrees of successful orientation.

As MIS typically relies on a 2D monitor interface, several orientational cues present when humans navigate in the real world are missing. These include inertial cues such as proprioceptive feedback, efference copies or vestibular information. It is therefore likely that effective orientation in MIS requires a different skill set and orientation strategy to that employed by humans navigating in their natural environment. There was no apparent difference in performance between different professions or sub-groups of medics (endoscopists v surgeons) perhaps reflecting the relative unfamiliarity of the spatial orientation task to all subjects. It is unlikely that neither laparoscopic surgeons nor endoscopists will have significant experience of these unique image manipulations within a spatial environment. Doctors with experience in NOTES may have enhanced these particular orientational skills however due to the novelty of the technique this sub-group did not feature in the experimental subjects.

The results of this experiment suggest that profiling visual fixation sequences based on HMMs can be confidently used to differentiate various orientation behavioural patterns. This experimental chapter corroborates theories regarding orientation proposed in the psychology literature and validates the algorithm for this purpose. The results of this experiment suggest that theories in the psychology literature on featural and geometric cues in place learning as well as concepts such as modularity have a directly translatable element to similar paradigms within MIS, and are highly relevant to understanding the problems and more importantly solutions to decreasing operator disorientation. The novelty of this research lies in the use of this particular profiling method which has previously not been utilised for eye tracking data and the potential application of this to orientation and in particular in the context of MIS, however it may be applicable and useful to other disciplines investigating orientation. This includes the study of 3D computer games, sports such as swimming, snorkelling and skiing, skyscraper building, parachuting and low gravity environments (and hence military and aerospace industries), and circus stuff such as tightrope or trapeze artists to name a few examples.

This experiment does have some limitations. Although the sample size was relatively small the data and behavioural diversity and performance was vast indicating high heterogeneity of both psychophysical behavioural patterns as well as outcome measures, thereby limiting this as a source of bias. Additionally, it is not known whether the results of this experiment are in any way translatable to a MIS scenario or whether expert surgeons have developed different or unique orientation strategies which cannot be profiled through temporal quantification methods such as the one used in this experiment. Another limitation of this experiment is that the images shown to the subject were not dynamic or controllable by the subject. Moving the camera and observing changes in the scenery may provide an important orientation strategy to some surgeons and furthermore when viewing a dynamic scene the orientation strategies employed may be different to those used when viewing a static one. Although this is acknowledged it was felt, as will be elaborated on in Chapters 4 and 6, that critical moments of orientation in MIS or instances when an error is likely to occur, are usually associated with disorientation to a relatively static scene and therefore with this applicability in mind it would be most useful first to evaluate orientation in this context.

The natural next step to follow on from the validation described in this chapter is to use this analysis framework to investigate orientation strategies in surgical scenarios, and whether these behavioural patterns are consistent when applied to expert surgeons during stages of surgical procedures associated with a risk of operator disorientation. Furthermore, when applied to real surgical scenarios, by profiling this behaviour it can be correlated with performance and therefore expert orientation strategies or behaviour which is associated with a high likelihood of success can be deduced.

Chapter 4 Evaluation of orientation strategies in laparoscopic cholecystectomy

This chapter is based on a study published in Annals of Surgery as referenced in introductory chapter.

4.1 Introduction

In the previous chapter, in accordance with currently held beliefs in the perception literature, gaze direction has been used as an indicator of attention in a visual environment [136] and it is now widely accepted that distribution of eye fixations are governed by intention and can therefore be related to attention [23] (provided that the eye movement is task-relevant as defined by Kahneman [24]). As outlined in Chapter 2, to obtain specific sensory information about our environment we have to focus our senses on that particular feature, therefore, the notion of focus of attention has a derived meaning referring to the physically observable behaviour of orientation towards an object. This may take the form of posture, head orientation and/or gaze. In the previous chapter as well as other studies of perception it has been demonstrated that analysis of eye tracking data allows a reliable identification of salient image features [137] that can be mapped back to spatial space for highlighting regions of interest and attention selection [125], and represents a method of knowledge gathering for decision support in image understanding [138].

In Chapter 3, it was shown that temporal fixation sequences could be profiled in a meaningful way whereby not only characteristics of the profiling embedding could be deduced but orientation strategies could be evaluated and quantified in the context of other outcome parameters such as orientation performance. By studying a surgeon's gaze in a situation where he or she is attempting to orientate may therefore provide clues of visual attention and strategies used during this process and similarly to the previous experiment, a correlation to performance should be possible.

In this chapter, the operation of laparoscopic cholecystectomy is used as the context in which orientation is evaluated in MIS. The reason for this is that it represents one of the more common applications of laparoscopic techniques and is now considered the gold-standard approach to cholecystectomy with up to 700,000 laparoscopic cholecystectomies performed yearly in the USA [139]. The second reason for investigating laparoscopic cholecystectomy, as described in Chapter 2, is that the major complication of bile duct injury which is associated with a mortality of 3% [109], a complication rate of 26% [110], has proven to be significantly associated with operator disorientation. Way et al [140] demonstrated that the errors leading to laparoscopic bile duct injury arise on the whole from a visual perceptual illusion and therefore disorientation, rather than errors in skill, knowledge or judgement. It is unfortunately impossible to calculate the proportion of bile duct injuries resulting from operator spatial disorientation due to the nature of the problem and the inherent lack of any such data in operative or patient records. The operator may lack insight into his or her orientational state, or may be unaware they were incorrect during the orientation process, however it is likely to account for a substantial proportion of this type of surgical complication.

Spatial disorientation is furthermore difficult to rectify when the operator is unaware they are disorientated, and this will be elaborated further in the discussion section of this chapter. However, when the operator does become aware of this, their ability to re-orientate correctly and effectively may play a major role in the outcome of the operation. Little is currently known about the factors that influence a surgeons orientational abilities including whether this is related to laparoscopic experience and/or seniority. No studies to date have examined or described specific strategies used for orientation during this operation or discussed the relation to outcome. This research is expected to benefit both trainee surgeons as well as experienced surgeons that consistently perform below average.

The hypotheses to be tested in this chapter were that there are common patterns of visual attention strategies employed by surgeons that are associated with a greater chance of successful reorientation when disorientated during laparoscopic cholecystectomy, and that seniority or laparoscopic experience will influence success at reorientation.

4.2 Methods

4.2.1 Subjects

The study was approved by the St.Mary's Research Ethics Committee (Ref: 08/H0712/104). All subjects were provided with an information leaflet and signed an appropriate consent form prior to commencement of the study. 21 surgeon subjects were recruited to take part in this experiment (19M: 2F). Mean age was 31.6 yrs (range 28 – 38 yrs). There were 4 consultants, 3 senior registrars and 14 junior registrars. For the purposes of an international readership, from here on in the thesis, consultant surgeons/attendings and specialist registrars/residents will be used interchangeably in the descriptions of levels of seniority. Table 1 illustrates the demographics and operative experience of the surgeons.

Table 4.1 Demographics and laparoscopic experience of subjects

	Mean age	**Mean number of laparoscopic operations as primary surgeon**	**Mean number of assisted laparoscopic operations**
Junior Residents	30	15	94
Senior Residents	34	107	250
Attendings	36	475	1400

4.2.3 Experimental design

During the experiment subjects were shown a series of 8 sequential images taken during human laparoscopic cholecystectomy operations from the operating laparoscope. The images represent typical views encountered during initial stages of a laparoscopic cholecystectomy up until division of the cystic duct divided into four image groups:

1. Overview of right upper quadrant structures
2. Close-up of right upper quadrant structures
3. Close-up of right upper quadrant structures with gallbladder retracted
4. Dissection of Calot's triangle

The images used for this experiment are illustrated in Figure 4.1. Three image groups contain the same images in various rotational transformations. The regions of interest of each image and their rotational orientation are given in Table 4.2.

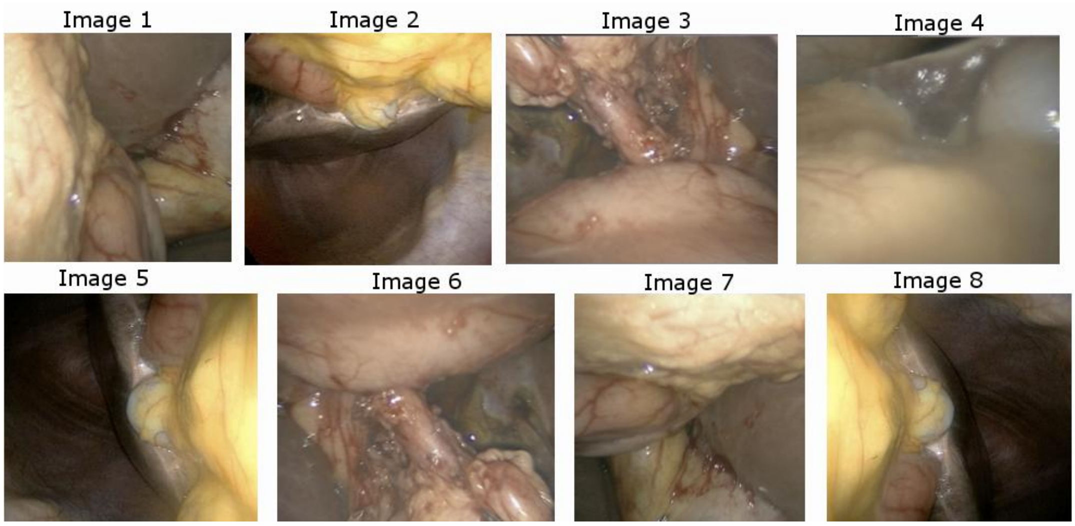


Figure 4.1 Visual stimuli used for experiment

Table 4.2 Image groups, stage of operation, relevant regions of interest in each group and orientational transformation as seen in Figure 4.1

Image Group	Stage of operation	Images	Regions of Interest	Orientation of Image
1	**Overview of RUQ structures**	2 5 8	GB, Peritoneum, Stomach, Omentum, Liver	2 - 180° 5 - 90° anti-clockwise 8 - 90° clockwise
2	**Close-up of RUQ structures**	4	GB, Peritoneum, Liver, Omentum	4 - Normal
3	**Close-up of RUQ structures with GB retracted**	1 7	GB, Liver, Stomach, Omentum, Calot's triangle (undissected)	1 - 90° clockwise 7 - 180°
4	**Dissection of Calot's triangle**	3 6	GB fundus, Cystic duct, Calot's triangle (dissected), Lesser Omentum, Stomach, Liver	3 - Normal 6 - 180°

GB- Gallbladder RU Q- Right upper quadrant

The aim was to disorientate the subjects with the introduction of the image and to observe reorientation behaviour. The images could only have been manipulated on a rotational axis in increments of 90° from a “normal” view (where contour of liver parallel to the horizontal or cystic duct almost vertical in dissection of Calot’s triangle). The “normal” view is the image orientation preferred by the vast majority of laparoscopic surgeons during this operation and this was described and illustrated with an unrelated laparoscopic image in the subject information sheet prior to commencement of the study. The task was to determine how, or if the images were manipulated with respect to their orientation. There was no time limit imposed on subjects to provide an answer for each image. Subjects controlled the progression of images via a keyboard and were given time between images to record answers on a sheet provided. Subjects were not told if their answers were correct or incorrect.

4.2.4 Eye-tracking

Similar to Chapter 3, gaze tracking was performed using a Tobii ET 1750 eye tracker (Tobii Inc, Sweden). As described, this is an infrared video-based binocular eye-tracking system recording the position of gaze in the work plane (screen) at 30 Hz. Infra-red light source is beamed towards the eye whilst a camera records the position of the reflection (known as the Purkinje reflection) on the cornea surface relative to the pupil centre. The infra-red images are real-time digitized and processed. Following a calibration procedure [29], the point of regard can then be determined with an accuracy of 1 degree across the work plane. This allows accurate tracking of the position of gaze of subjects standing approximately 60cm away from the equipment looking at the monitor. Fixations were detected using a dwell time algorithm by which a fixation is considered when the gaze does not move more than a hard threshold (30 pixels), during a minimum of a 100ms [29].

As the participants are shown each new image stimulus to discern its orientation, their eye-gaze navigates between the organs and structures in the scene exposing differences in visual behaviour. We analysed these differences in visual behaviour using the algorithm which was detailed and validated to use for the purpose of comparing visual reorientation behaviour in the previous chapter. To summarise, the output of this algorithm produces a two-dimensional graph plotting the behaviour of each subject as a single point. Points in close proximity in the output plot are shown to demonstrate similarity in visual reorientation behaviour and by examining gaze plots the significance of moving across the two axes can be inferred. The classic k-means algorithm [141] was used to compute the centroids for the subject groups who answered correctly in each image and the closest subject the centroids of this group was selected as the most representative to discern the average successful reorientation strategy for each image.

4.2.5 Behavioural Data

Each image or stimulus was manually segmented into ROIs delimiting the different significant organs and structures. The outcome parameters of this study were time taken to provide each answer, whether the answer was correct / incorrect, and basic eye-tracking parameters such as fixations and dwell-time per ROI. Other outcome parameters were fixation sequences on ROIs as determined by organs and structures occupied in the scene and the order in which these were fixated upon. To normalize the dwell time per region of interest this was divided by the relative area occupied by that structure within each image.

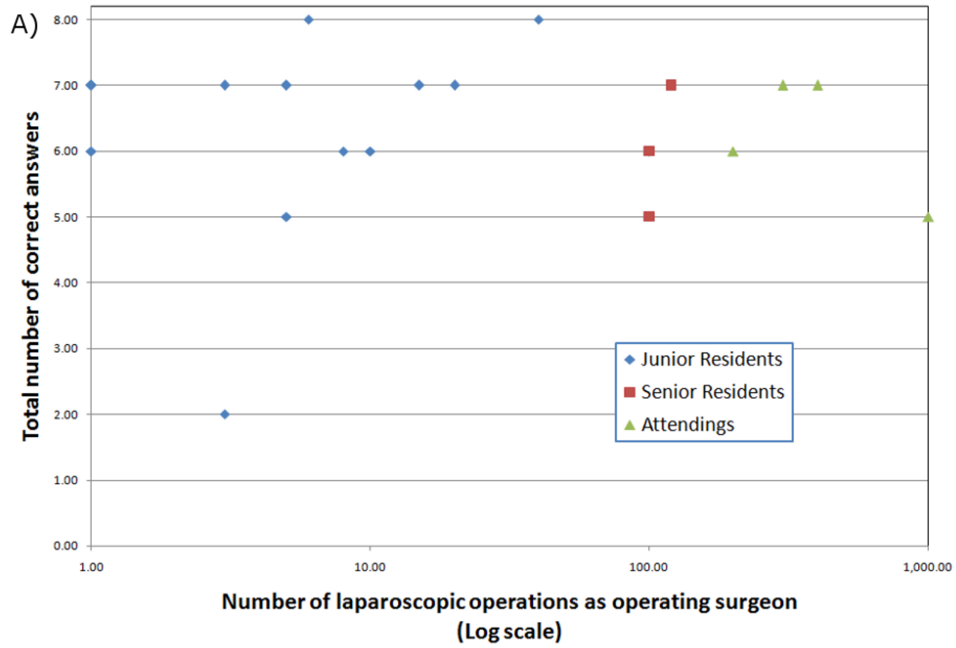
4.2.6 Statistics

Comparisons between groups of non parametric variables were done using the Kruskal Wallis test with individual variables compared using the Mann Whitney U test as necessary. Correlations of continuous variables were determined by non-parametric linear regression. All analyses were performed using statistical software (SPSS v16.0, Chicago, USA). Differences were considered statistically significant at $p<0.05$.

4.3 Results

4.3.1 Overall orientation score

Junior registrars, senior registrars and consultant surgeons answered an average of 6.36 (range 2-8), 6 (range 5-7) and 6.25 (range 5-7) out of 8 correctly respectively. There was no statistically significant difference in number of correct answers between these groups ($p=.919$). There was no significant correlation between number of previously performed laparoscopic operations as first surgeon ($p=.78$; $r^2=-0.065$) or assistant ($p=.257$; $r^2=-0.259$) with the number of correct answers given as is illustrated in Figure 4.2). Eight subjects were aware that they adopted a specific reorientation strategy. There was no difference in number of correct answers given between subjects who declared they were aware of a reorientation strategy and those who did not ($p=.795$).



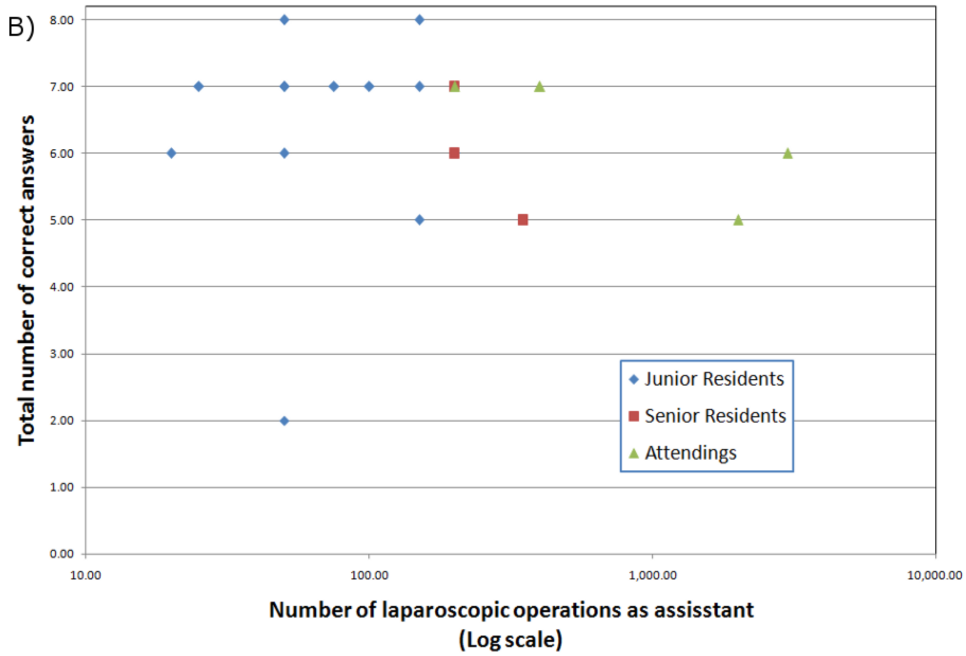


Figure 4.2 Scatter plots of number of correct answers against number of laparoscopic operations as a) operating surgeon and b) assistant

4.3.2 Eye tracking parameters

Eye tracking parameters was analyzed from two perspectives as illustrated in tables 3 and 4:

1) seniority of subjects (3 groups)
2) number of correct answers given (5 groups)

Table 4.3 Comparison of basic eye tracking parameters by seniority of subject

	Junior Residents	Senior Residents	Attendings	P
Mean time taken to answer (sec)	20.9	18.2	12.4	0.174
Mean number of fixations	41.9	45.8	29.2	0.123
Mean absolute dwell time / ROI (ms)	2309	3197	1836	0.78
Mean normalised dwell time (ms/pixels^2) /ROI	1.99	2.3	2.1	0.997

Table 4.4 Comparison of basic eye tracking parameters by total number of correct answers of subjects

	Number of Correct Answers (/8)					
	2	5	6	7	8	**P**
Mean time taken to answer (sec)	15.5	19	16.5	20.4	21	0.174
Mean number of fixations	22.5	38.3	41	38.2	56.3	0.123
Mean absolute dwell time / ROI (ms)	1923	1774	2624	2273	2893	0.004
Mean normalised dwell time(ms/pixels^2)/ ROI	1.72	2.12	2.09	2.12	1.74	0.911

It can be seen that when mean dwell time per ROI was normalized there was no difference by seniority or performance groups.

Since the performance between seniority groups were not significantly different for this experiment the mean normalised dwell time between all groups was used for further analysis. The dwell times on individual organs and structures has been analysed for different stages of the operation as detailed in Table 4.2.

4.3.3 Visual behaviour profiling & average successful reorientation behaviour

It is naturally anticipated that individual surgeons may use different successful reorientation strategies but to discern a generalizable average successful behaviour the subject closest to centre of gravity of the group who answered correctly was chosen as the most representative behaviour.

The centre of gravity represents the mean or central point of the cluster as computed by the k-means algorithm.

The image results are presented below in the order in which they are encountered during the operation:

4.3.3.1 Overview of right upper quadrant structures - Images 2, 5 & 8

As shown in Figure 4.3a and 4.3b there appeared to be similar amounts of attention by dwell-time across the images indicating the use of a comparable and consistent orientation strategy across subjects and seniorities. During overview of right upper quadrant structures, surgeons focused heavily on the position of the gallbladder, liver and the stomach for reorientation. It appears that when the image is manipulated by 90° the attention paid to the gallbladder increases to a maximum when the image is rotated clock-wise.

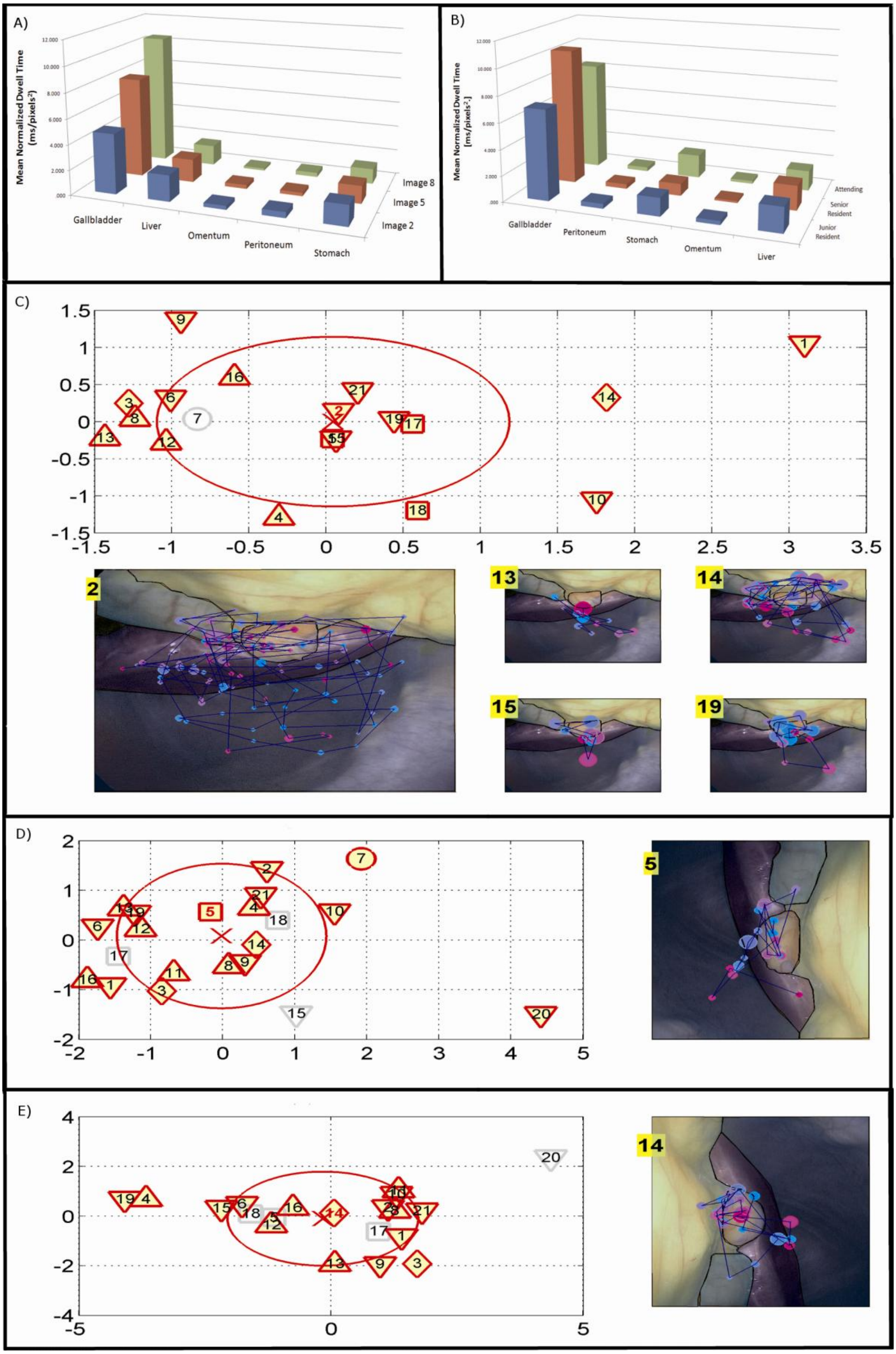

A)
Mean Normalized Dwell Time [ms/pixels²]
Gallbladder
Liver
Omentum
Peritoneum
Stomach
Image 8
Image 5
Image 2
B)
Gallbladder
Peritoneum
Stomach
Omentum
Liver
Attending
Senior Resident
Junior Resident
C)
D)
E)

Figure 4.3 a) Mean normalized dwell times per region of interest in stimulus images 2, 5 & 8. **b)** Mean normalized dwell times per region of interest for the image group per subject seniority. **c)** Example of the visual path profiling algorithm output illustrating subject performance (circle=2 total correct, squares=5, upward pointing triangle=6, downward pointing triangle=7 & diamonds=8), and answer, (yellow shading=correct answer, no shading=incorrect answer) for the stimulus image 2. Subject numbers are represented within shapes. Centroids are illustrated by cross in the middle of sphere for subjects who answered correctly. Closest subject identified by highlighting number red. Relevant gaze plots are shown for selected subjects with initial fixations coded in blue turning to red to the end of the fixation sequence. **d)** Output of visual path algorithm for stimulus image 5. Coding is as for Figure 4.3c. **e)** Output of visual path algorithm for stimulus image 8. Coding is as for Figure 4.3c

The profiling output in Figure 4.3c confirms the relative importance of the gallbladder as a visual cue for reorientation in this image as established by the high mean normalized dwell time displayed in Figure 4.3a. The fact that most surgeons correctly orientated in this scenario is likely to reflect the familiarity of this view. The majority of subjects use the gallbladder as an "anchor object" and relate the relative positions of the liver and stomach to this during orientation. The majority of subjects additionally used the peritoneum of the abdominal wall and diaphragm and the omentum to a lesser extent as additional cues as seen by the gaze plots close to the centre of gravity in Figure 4.3c. By examining the gaze plots as we move across the abscissa axis in Figure 4.3c it can be seen that the gallbladder remains a central visual cue. As illustrated by gaze plots of subjects 13, 15, 2 and then 14 by moving from left to right across this axis the focus of attention to peripheral reference structures changes from the peritoneum of the diaphragm and anterior abdominal wall to the greater omentum. It is important to highlight that the profiling plots capture both the spatial distribution of fixations as well as the temporal aspect of the order on which structures are fixated upon. To that end, it is possible to quantify the orientation strategy. In Figure 4.3c the most representative behaviour is that illustrated by subject 2 however this fixation sequence is quite long and therefore difficult to quantify visually nonetheless subject 15 is very close to the centre of gravity point and the strategy employed by this subject is easily discernable. Initially the gallbladder is identified and its position is related to the liver, stomach, the greater omentum and finally the peritoneum of the diaphragm. An almost identical strategy is displayed by subject 19.

Figure 4.3d clearly illustrates the strategy adopted by subject 5 in reorientation. This involves initial identification of the gallbladder and thereafter relating positions of liver, stomach and ultimately peritoneum of the abdominal wall to the position of the gallbladder to deduce correct orientation of the image. An almost identical strategy is displayed by subject 14 in Figure 4.3e confirming the reliability of this methodology to evaluate successful behaviour.

4.3.3.2 Close up of right upper quadrant structures – Image 4

As shown in Figures 4.4a and 4.4b, it appears that when surgeons are confronted with a limited view of organs in the right upper quadrant, identification and orientation by the position of the liver is common and important with similarities of focus across seniority levels although consultant surgeons appear to focus somewhat more on the gallbladder. Figure 4.4c illustrates the homogeneity of orientational behaviour which appears to focus heavily on the position of the liver relative to the gallbladder with some attention placed on relative positions of omentum. Comparatively little attention is paid to the peritoneum of the abdominal wall, probably reflecting the difficulty of using this structure as an effective visual cue in this scenario. The importance of attention to the liver and gallbladder corresponds well with the overall high mean normalized dwell times shown in Figure 4.4a.

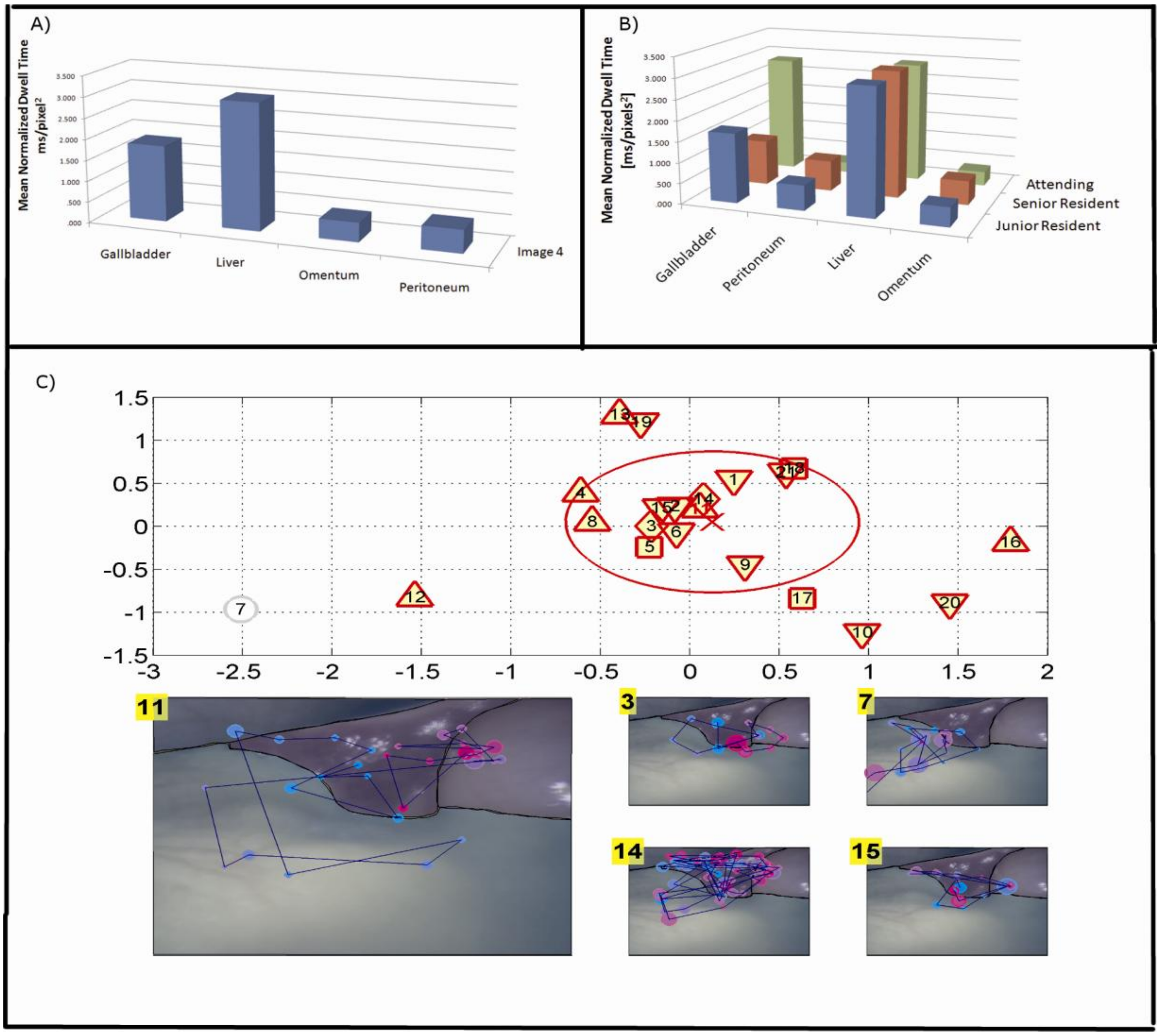


Figure 4.4 a) Mean normalized dwell times per region of interest in stimulus image 4. **b)** Mean normalized dwell times per region of interest per subject seniority. Note registrar and consultant correspond to resident and attending **c)** Output of visual path algorithm for stimulus image 4. Coding is as for Figure 4.3c

Subject 11 clearly illustrates the average successful orientation strategy used starting by identifying the liver and relating relative positions of the gallbladder and other structures to this. Subject 7 adopted an unsuccessful reorientation strategy and the reason for this is revealed when examining the gaze plot. The liver and omentum were the only structures focused on by this subject with no attention paid to the position of the gallbladder, which makes it more difficult to establish correct orientation.

4.3.3.3 Close-up of right upper quadrant structures with gallbladder retracted - Images 1 & 7

As shown in Figure 4.5a the normalized dwell time profile is consistent across both images with similar dwell-time for Calot's triangle, the gallbladder and the stomach across both images with less attention paid to the liver and omentum. This again suggests that subjects used similar and coherent strategies for this view despite different image transformations. Figure 4.5b shows similarities in dwell time profiles across seniorities.

Figure 4.5c illustrates the visual behaviour profiling revealing the various reorientation strategies used in this scenario. Moving from left to right across the abscissa axis subject 4 prioritises the liver and omentum whilst on the other end of the axis subject 1 almost completely disregards the omentum as a reorientation cue but focuses heavily on liver, gallbladder and Calot's triangle. Subject 10 displays a unique strategy focusing heavily on the stomach as a visual re-orientational cue. Subject 3 lies close to the centre of gravity of successful subjects and when examining the gaze plot it can be seen that this corresponds well with the overall mean normalized dwell times.

When examining Figure 4.5d the same trend becomes apparent. Moving across the abscissa axis shifts the subjects focus from the liver towards the gallbladder with decreasing amounts of fixations on the omentum. Subject 2 lies close to the centre of gravity of successful subjects and the gaze plot also appears to correspond well with average dwell time behaviour with much focus on Calot's triangle, gallbladder and stomach in seemingly equal proportions with less attention on the omentum and liver. Subject 21 illustrates an uncommon behaviour whose reorientation strategy appears to completely ignore Calot's triangle.

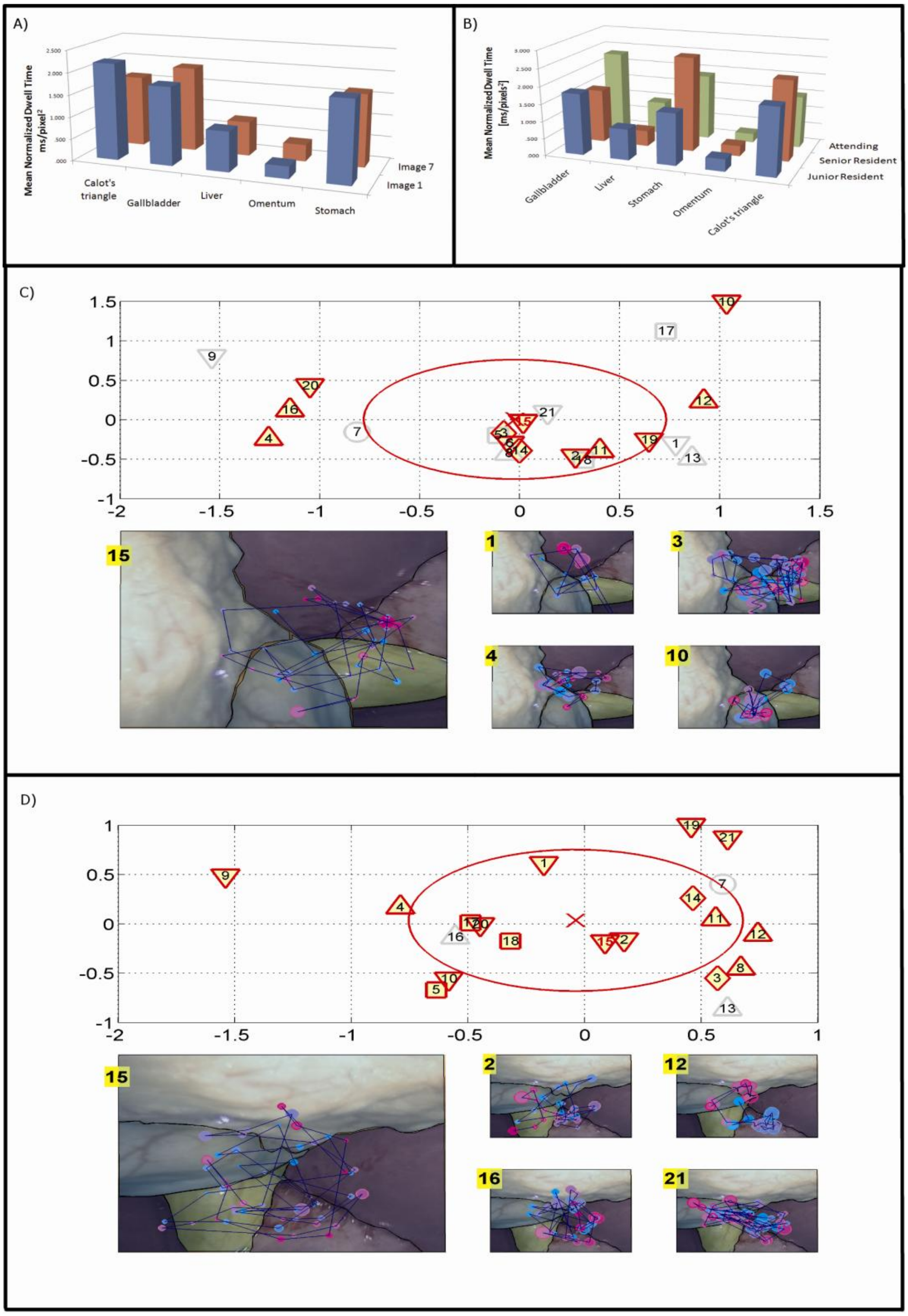


Figure 4.5 a) Mean normalized dwell times per region of interest in stimulus images 1 and 7. **b)** Mean normalized dwell times per region of interest per subject seniority. Note registrar and consultant correspond to resident and attending **c)** Output of visual path algorithm for stimulus image 1. Coding is as for Figure 4.3c. **d)** Output of visual path algorithm for stimulus image 7. Coding is as for Figure 4.3c.

The average successful reorientation behaviour is illustrated in Figures 4.5c and 4.5d which both show that the visual reorientation strategy of subject 15 was the closest to the mean behaviour of successful subjects in both images 1 and 7. By looking at the gaze plots of this subject in both images it can be seen that an almost identical reorientation strategy was used in both images. This involved initial identification of liver, stomach, gallbladder, omentum and then Calot's triangle in turn followed by alternating fixations on mainly the gallbladder, Calot's triangle and stomach to deduce orientation.

4.3.3.4 Dissection of Calot's triangle - Images 3 & 6

This group represents close-up images of a dissection of Calot's triangle with a clearly visible cystic duct. Subjects appeared to focus heavily on the cystic duct and relating this to the positions of the dissected Calot's triangle or the lesser omentum. The similarities in dwell time across both images and seniorities are again very apparent in Figures 4.6a and 4.6b.

In Figure 4.6c there appears to be substantial clustering of subjects who answered the question correctly. On closer inspection of these gaze plots it is apparent that these subjects relied heavily on the cystic duct as a reorientation cue apparently using this as a reference to the position of Calot's triangle and the lesser omentum between the liver as clearly illustrated by the gaze plots of subjects 3, 14, 18 & 21. Subject 4 applied an unsuccessful strategy and it can be seen that there is much less focus on the position of the cystic duct and no attention given to Calot's triangle.

A similar pattern of behaviour is observed in Figure 4.6d. The visual behaviour of subject 12 illustrates an unsuccessful reorientation strategy with heavy focus on the position of the liver to the cystic duct, which of course would not allow differentiation between 180° rotations.

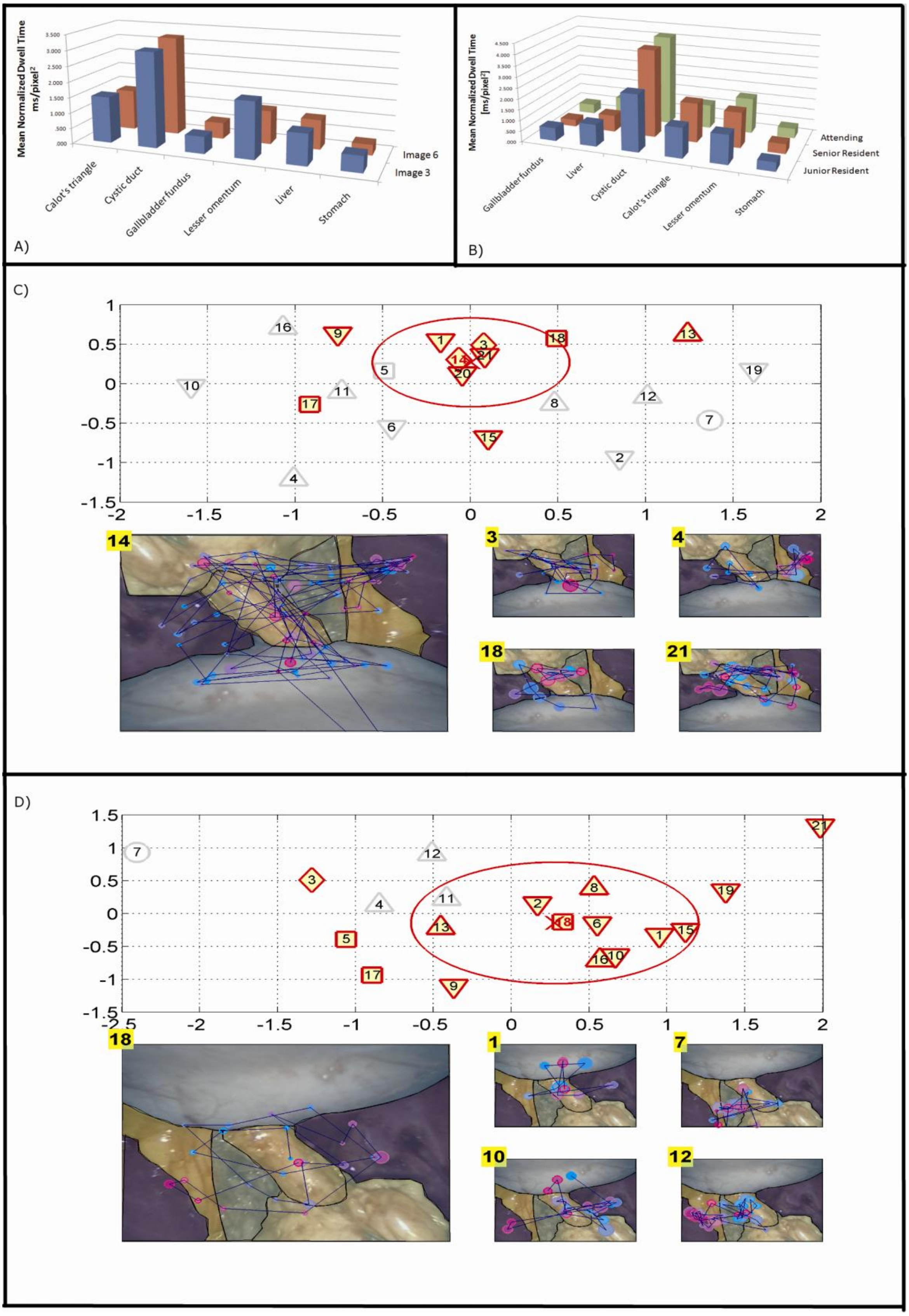

A)
Mean Normalized Dwell Time ms/pixel²
Calot's triangle
Cystic duct
Gallbladder fundus
Lesser omentum
Liver
Stomach
Image 6
Image 3
B)
Mean Normalized Dwell Time [ms/pixel²]
Gallbladder fundus
Liver
Cystic duct
Calot's triangle
Lesser omentum
Stomach
Attending
Senior Resident
Junior Resident
C)
D)

Figure 4.6 a) Mean normalized dwell times per region of interest in stimulus images 3 and 6. **b)** Mean normalized dwell times per region of interest per subject seniority. Note registrar and consultant correspond to resident and attending **c)** Output of visual path algorithm for stimulus image 3. Coding is as for Figure 4.3c. **d)** Output of visual path algorithm for stimulus image 6. Coding is as for Figure 4.3c.

Due to the relative complexity of this scenario the fixation sequences to orientate tended to be longer than in other scenarios, however using the gaze plots in Figures 4.6c and 4.6d such as that of subject 18 in combination with the information of the normalized dwell times per ROI, it is nevertheless possible to accurately describe a representative successful behaviour. This involved initial identification of the cystic duct, followed by identification and relation of the lesser omentum to the cystic duct, followed by the liver, stomach, Calot's triangle and finally gallbladder fundus to deduce orientation. It is apparent that after identification of a structure this is related by a subsequent fixation on the cystic duct used as "anchor" object.

From Table 4.5 it can be seen that apart from the first image, when subjects were familiarising themselves with the experimental task and set-up, image group 4 (images 3 & 6) appears to be the most complex illustrated by higher number of fixations and event durations than other image groups.

Table 4.5 Mean number of fixations and event duration per image

	Image Number							
	1	2	3	4	5	6	7	8
Number of Fixations	76	24	71	31	17	47	37	17
Event Duration (sec)	34.011	11.330	32.308	15.111	9.823	20.870	17.997	9.908

4.4 Discussion

The results of this chapter indicate that there are discernable and quantifiable visual attention strategies used by surgeons during laparoscopic cholecystectomy associated with successful orientation. There was no difference in success in reorientation between different seniorities and laparoscopic experience of the surgeon subjects. This finding is corroborated by the lack of grouping of subjects in the visual profiling outputs between seniorities or laparoscopic experience. In some instances however, there was grouping of subjects who orientated successfully on a particular image, indicating similar individual strategies, as illustrated in Figure 4.6c. Although performance results were homogeneous across seniority groups in this study, increased subject numbers or a greater breadth of experience between the subject groups may have demonstrated a difference in performance. Given the present results however, this was deemed unnecessary as the main aim of this experiment was to characterise effective behaviour. It is important to note that all subjects had significant laparoscopic experience as assistants if not as primary surgeons. The homogeneity of performance across experience levels suggest that after a certain level of laparoscopic experience surgeons reach a plateau consistent with their innate orientational abilities. This is consistent with the finding that bile duct injuries have appeared to remain constant over recent years despite improvements in surgical instruments and visualization equipment [109]. As it is thought that the majority of bile duct injuries occur as a result of spatial disorientation [112], the implication of this is that the risk of bile duct injury as a result of disorientation is intrinsic to the operation due to the innate abilities of surgeons. It is therefore important to note that in this study even the most experienced surgeons were mistaken on average 22% of the time in the orientation process. This is not a trivial percentage and reflects the importance of this issue in relation to laparoscopic surgery.

As expected, there were individual differences in both visual attention strategies used and performance outcome. This correlates well with findings in the psychology literature which suggest there is a wide range of performance in relation to orientation with age and sex being contributing factors as well as the features of the spatial environment [58-61].

It is intuitive that the initial fixations when presented with a novel scenario is to correctly identify the relevant anatomical structures, and the time taken and relative focus of this will differ between individuals. In this study it is assumed that surgeons correctly identified most relevant anatomy, and it is recognized that detection of a familiar scene by an individual may only require a few carefully placed fixations. Nevertheless, this experiment attempts to discern behaviour after anatomy recognition when attention strategies are employed to achieve orientation. With this in mind, it was shown that for all scenarios presented of a laparoscopic cholecystectomy there appeared to be a common strategy used by a large proportion of surgeons which was associated with a high chance of successful reorientation. The combination of images used in this study represents many of the common views faced by a surgeon during a laparoscopic cholecystectomy. It was very apparent that choosing an “anchor object” and relating position of selected structures to this was an almost a uniformly successful orientation strategy. This appears to be a common human orientation strategy, as this was very commonly employed by subjects in the previous chapter, which had no relation to laparoscopic surgery or human anatomy. The choice of anchor object and related structures was different during various stages of laparoscopic cholecystectomy and the results of this experiment suggest that this choice can determine the outcome of the orientation process.

It was clear that when viewing the organs of the right upper quadrant the relative position of the gallbladder as an “anchor object” to the liver and stomach was a very powerful and successful orientation strategy. When the gallbladder was retracted the choice of anchor object became less clear and it appeared that either use of the gallbladder, stomach or the region of Calot’s triangle as long as they were related to the position of the other two structures proved to be effective in orientation. Surgeons who correctly reorientated when presented with an image of a dissected Calot’s triangle almost exclusively used the position of the cystic duct as an “anchor object”. This is unlikely to represent a featural cue as the position of the duct within the image will not correctly identify orientation however what appears important is likely to first be the geometry of the duct i.e. if the duct is relatively vertical the image must be normal in orientation or rotated 180°, and thereafter the relative position of the duct to surrounding structures such as the lesser omentum and stomach, which will differentiate between these transformations. The fact that graphs of mean normalized dwell times per ROI of the same image in different rotations are almost identical provides strong evidence that whatever the rotation of an image presented to a surgeon, the relative importance of ROI’s are consistent and similar between transformations.

It was interesting to note that on questioning only a minority of surgeons (8/21) were actually aware that they adopted a particular orientation strategy. This further supports the idea that this represents an automated phenomenon in the majority, which has been cognitively programmed through experience. This study assumed that surgeons did not have an advantage over each other with regards to their cognitive map, which in this case represents their knowledge of the correct anatomy concerned with the operation, as all subjects had completed specific surgical postgraduate examinations containing relevant surgical anatomy and have operative experience in relation to laparoscopic cholecystectomy.

By using the analysis framework validated in the previous chapter, and considering both overall normalized dwell times per ROI and the average successful fixation sequences in combination, successful orientation strategies have been accurately described and quantified.

In the previous chapter, reorientation was investigated in a more diverse population of subjects, without a previously formed cognitive map of the scenery prior to the experiment, and not necessitating the use of knowledge of human anatomy. This showed a more varied difference in performance between individuals but highlighted some common strategies. When this experimental paradigm was applied to laparoscopic surgery as in this study, successful reorientation appeared to be more prevalent reflecting the familiarity of this paradigm and task to many surgeons.

It is important to point out that using eye-tracking for research into human attention processes carries some known assumptions and limitations. Because attention is composed of both higher and lower level functions it is well known that humans can voluntarily dissociate attention from their foveal direction of gaze [25]. This high level component of vision is obviously much more difficult to detect by objective external observation. Therefore, the important assumption that attention is linked to foveal point of gaze is usually made in eye-tracking experiments. We believe that this assumption holds true especially if the right experimental conditions are met. In this experiment we believe this is the case because visual attention selection is driven by a top-down mechanism and is therefore derived from task specification i.e. the orientation process, rather a reactive mechanism caused by salient stimuli (bottom-up). The eye tracking equipment used in this study is a remote video-oculography (VOG) based system integrated with a normal computer screen, and therefore does not change the normal navigation behaviour of the subjects. It can cater for head movement and there were no concerns from subjects regarding the adequacy of the equipment. It is worth noting that like all existing state-of-the-art eye-tracking systems, our setup does require a subject specific calibration step at the beginning of the experiment. Further research is necessary in developing techniques that can significantly simplify or potentially remove this step.

Disorientation and therefore patient morbidity may occur in a number of scenarios during a laparoscopic cholecystectomy. Firstly, the operator may not be aware they are disorientated. This may happen if the anatomy encountered is not normal. Secondly, the operator may have incorrectly identified some anatomical structures resulting in disorientation which may or may not be realized, and thirdly, the operator may just be “lost” with identification of some or all anatomy correctly resulting in realized disorientation. We believe the results of this study have relevance to all the variations of disorientation described above.

By exposing visual behaviour and by inference attention processes of surgeons, this study represents an initial step in attempting to decrease the effects of disorientation in laparoscopic surgery and further innovations in MIS. This study raises some important questions. Firstly, can these common reorientation strategies be taught to aspiring surgeons as part of a curriculum thereby decreasing the learning curve associated with the apparent need for experience in laparoscopy? Secondly, can these common reorientation strategies be taught to individual surgeons who performed below average to increase their performance? Should this be the case, teaching reorientation strategies should be incorporated into the laparoscopic teaching curriculum for surgical trainees. The next step in the investigation of this paradigm will be to evaluate whether performance can be improved in a prospective, randomised controlled trial of teaching orientation strategies unveiled in this chapter.

Chapter 5 Orientation training in laparoscopic cholecystectomy – a randomized controlled trial

This chapter is based on a study published in the British Journal of Surgery and presented at the Association of Surgeons of Great Britain and Ireland Annual Scientific Meeting in Bournemouth 11-13 May 2011 as referenced in introductory chapter.

5.1 Introduction

As outlined in the introduction and illustrated experimentally in subsequent chapters, operator disorientation is an increasingly recognized problem in MIS, as the complexity involved results in a greater cognitive load on the surgeon. As has been detailed previously in this thesis, little research has thus far been dedicated to quantifying disorientation or its implications in laparoscopic surgery, however it has been suggested that up to 97% of errors during laparoscopic cholecystectomy are due to a visual perceptual illusion, not necessarily faults in technical skill, knowledge or judgement [140]. There are many factors contributing to an action such as the erroneous division of a duct, and in relation to laparoscopic surgery many of these contributing factors are unknown. As mentioned in the introductory chapter, the psychology literature offers some insight into the decision-making process contributing to the execution of erroneous decisions. Theoretical psychology pioneered by Jerry Fodor refers to the theory of modularity [59,62,63,65] whereby each decision making process has a number of “input systems” or sensory feeds which in turn provide output to a central decision-making system. Establishing correct orientation may be only one module that contributes to a central system in executing an operative decision. Nevertheless, it is intuitive that the decision not to divide a structure which is not the correct one is facilitated by correct spatial orientation.

In the study described in Chapter 4 eye-tracking data was used to evaluate, describe and quantify visual orientation behaviour of surgeons during specific stages of laparoscopic cholecystectomy. The orientation strategies associated with high performance were described, and the importance of focusing on specific organs or regions of interest (ROIs) during each stage of the operation was determined. The results suggest that surgeons reach a plateau of orientational performance in keeping with their innate ability prior to or at an early stage of the United Kingdom higher surgical training / residency programme, which is usually started 4-5 years post graduation and following 3 years of basic surgical training. In modern surgical training curriculums trainees climb the learning curve of laparoscopic cholecystectomy under supervised conditions. Because of this and the inherent reporting bias of bile duct injuries, as well as multiple confounding factors, there is little robust evidence associating bile duct injuries in laparoscopic cholecystectomy with operative experience [142,143]. Given the apparent lack of difference in orientational abilities, it can be argued that experience will equip the surgeon with enhanced proprioceptive awareness (other “input systems”) contributing to a decision of not dividing a structure erroneously which the novice surgeon may lack.

In this chapter, the question of whether orientation training is feasible and whether this training can make a difference to orientational skills is addressed. This research was conducted by means of an orientation task posed to a control group receiving no training, as well as an intervention group receiving specific orientation training. It is hypothesized that specific high performance orientation strategies can be taught to an undifferentiated (without medical sub-specialization) subject group of final year medical students without significant experience of laparoscopic cholecystectomy to increase orientational performance. The consequence being a reduction in the operative experience or learning curve required to grasp this skill and the acquisition of a new skill set applicable to other laparoscopic scenarios such as other operations, abnormal anatomy or diseased tissue, and therefore a presumed improvement in patient safety and operative morbidity. The aims of this study were to compare orientational performance and psychophysical visual behaviour in subjects who were taught high performance strategies against a control group who were not.

5.2 Methods

5.2.1 Study participants

30 final year medical students with no visual impairment were recruited for this study which was carried out in the Perception & Ergonomics Laboratory at Imperial College London. The study was approved by the local research ethics committee and participants provided appropriate consent prior to inclusion. Subjects completed a questionnaire prior to the study detailing demographics, percentage marks gained in medical school anatomy and surgical examinations, additional anatomy training, previous experience of laparoscopic cholecystectomy and future career aspirations.

5.2.2 Experimental design

Eligibility criteria included final year medical students without significant visual impairment. Participants were randomized to either intervention or control by allocation of a concealed envelope in a 50:50 allocation ratio. The randomization sequence was computer generated in blocks of 10 and the investigator assessing the outcomes was blinded to group assignment as study groups were not recorded on orientation answers or eye tracking data. Separate investigators generated the random allocation sequences / assigned participants to intervention to enrolling participants.

The participant information sheet given to all subjects detailed the experimental design, clarified the “normal” rotational view during laparoscopic cholecystectomy, where the liver contour is parallel to the horizontal or cystic duct almost vertical in dissection of Calot’s triangle, and also illustrated the three main stages of the operation evaluated during this experiment with a laparoscopic image of each stage which was unrelated to the experimental images.

During the experiment, subjects were shown a series of 12 sequential images taken during laparoscopic cholecystectomy from a 0° operating laparoscope illustrated in Figure 5.1. The images were randomly ordered but represented typical views encountered during the operation and consisted of four groups of three identical images in various rotational transformations. The aim was to disorientate the subjects with the introduction of the image and to observe reorientation behaviour. To ensure comparability of data, the main experimental design was identical to that used in Chapter 4 which quantified orientation strategies during this operation. However, an additional 3 image rotations were introduced in separate image groups.

The images could only have been rotated in increments of 90° from the "normal" view. The task was to determine if or how the images were manipulated with respect to their orientation. There was no time limit imposed on subjects to provide an answer for each image and they were not told if answers were correct or incorrect. Subjects themselves controlled the progression of images via a keyboard and recorded written answers between the images on a sheet provided. There were no changes to methods after trial commencement.

Figure 5.1 Visual stimuli used in the study. Four stages of the procedure are presented under different rotational views to induce disorientation.

5.2.3 Behavioural data and sample size

Each stimulus image was manually segmented into ROIs delimiting significant organs and structures. The primary outcome measure of this study was the number of correct answers provided by each subject i.e. their orientation performance. Secondary outcome measures included time taken to provide each answer, gaze dwell-time on each ROI, and individual subject fixation sequences on ROIs in each image. Gaze dwell time on each ROI was normalized by the relative area occupied by that structure within the image [seconds/pixels^2].

Following a pilot study of 11 subjects, a power calculation based on the difference in primary study outcome between the groups indicated the need for a minimum of 29 subjects for 80% power and a type 1 error rate of 0.05 with an estimated effect size of 0.798.

5.2.4 Intervention

The intervention consisted of a 13 minute tutorial video presentation. In the tutorial, specific orientation strategies used during four stages of the operation that were associated with successful orientation learnt from the data presented in the results of Chapter 4 were presented.

For each stage of the operation, the tutorial video illustrated:

1. Salient regions of interest / organs to identify and their importance, and in particular the best ROI to use as an "anchor organ" during the reorientation process. This represents the orientational strategy taught and entails focusing on one particular ROI (the *anchor* organ) and subsequently relating the position of other specific ROIs (*peripherals*) to this to deduce correct orientation.
2. Other important organs, *peripherals* to the anchor, to identify during each particular stage of the operation and the need and importance of relating their position to that of the anchor object and other significant ROIs to deduce orientation.
3. The characteristics of individual ROIs that should be used to distinguish orientation when related to other ROIs.
4. Exemplary gaze fixation sequences associated with a high chance of successful reorientation.

The tutorial was designed aiming not to confer an unfair advantage by teaching additional operative anatomy. As such, only the 3 laparoscopic images also used in the participant information sheet were used in the tutorial to demonstrate the learning points visually. Orientation strategies were thereafter described in writing and illustrated using schematic drawings.

Subjects allocated to intervention completed the experiment immediately after having watched the tutorial presentation.

5.2.5 Eye tracking and gaze modelling

Gaze tracking was performed using the same infrared video-based binocular eye-tracking system (ET 1750, Tobii Inc, Sweden) used in previous chapters which recorded the point of gaze in the monitor at 30 Hz. These differences in visual behaviour exposed by gaze patterns were analysed using the algorithm previously detailed and validated for the purpose of comparing visual reorientation behaviour in chapter 3 and subsequently used for behavioural profiling in Chapter 4. Briefly, the output of this algorithm encapsulates the visual behaviour of each subject as a single point within a 2D chart referred to as behaviour profiling output graphs. Spatial location of the points is concomitant with the strategy adopted, e.g. which anchor object and which peripherals. Points in close proximity in the**se** output graphs demonstrate similarity in visual behaviour and by examining individual subject gaze plots (sequence of fixations on the image) their visual behaviour can be described.

5.2.6 Statistical analysis

Comparisons between groups of non parametric variables were performed using the Kruskal Wallis test with individual variables compared using the Mann Whitney U test as necessary. Categorical variables were compared using the Chi squared test. All analyses were performed using statistical software (SPSS v18.0, Chicago, USA). Differences were considered statistically significant at $p<0.05$.

5.3 Results

5.3.1 Overall performance

30 subjects (9F:21M) were randomly assigned to two groups of 15 subjects during the study period of May & June 2010. All subjects who enrolled completed the study protocol and were analyzed for primary and secondary outcome. All analysis was by original assigned groups and the trial was ended when the calculated sample size had been reached. Table 5.1 shows a comparison of the demographics of each group.

Table 5.1 Demographics and experience of subjects

	Control	**Intervention**	**P**
Age (median)	23	22	0.878
Sex	10M:5F	11M:4F	0.690
Median grade anatomy examination (%)	67.5	69	0.346
Median grade clinical surgery examination (%)	74.5	79	0.205
Additional anatomy experience (/15)	3	2	0.624
Median number of cholecystectomies seen before	3	3	0.661
Interested in a career in surgery (/15)	9	6	0.273

The intervention group recorded a median of 10 out of 12 correct answers (mean = 9.07; range 3-12; 95% CI 7.62 - 10.51) and the control group recorded a median of 6 out of 12 correct answers (mean = 6.73; range 3-11; 95% CI 5.29 – 8.18). The intervention group recorded a significantly greater total number of answers correct compared with the control group (p=0.019) and were significantly more likely to correctly deduce orientation of individual images (p=0.0001). Table 5.2 illustrates the four image groups used as stimuli, the ROIs in each image and correct rotational transformation. The intervention group also took on average longer to study each image stimulus before producing an answer than the control group (median 24.0 v 19.8 sec; p=0.01).

Table 5.2 Image groups, stage of operation, relevant regions of interest in each group and orientational transformation as seen in Figure 5.1

Image Group	Stage of operation	Images	Regions of Interest	Orientation of Image
1	**Overview of RUQ structures**	2 5 8	GB, Peritoneum, Stomach, Omentum, Liver	2 - 180° 5 - 90° anti-clockwise 8 - 90° clockwise
2	**Close-up of RUQ structures**	4 9 12	GB, Peritoneum, Liver, Omentum	4 - Normal 9 - 90° clockwise 12 - 90° anti-clockwise
3	**Close-up of RUQ structures with GB retracted**	1 7 10	GB, Liver, Stomach, Omentum, Calot's triangle (undissected)	1 - 90° clockwise 7 - 180° 10 - 90° anti-clockwise
4	**Dissection of Calot's triangle**	3 6 11	GB fundus, Cystic duct, Calot's triangle (dissected), Lesser Omentum, Stomach, Liver	3 - Normal 6 - 180° 11 - 90° anti-clockwise

GB- Gallbladder RUQ- right upper quadrant

5.3.2 Overview of the right upper quadrant

Figure 5.2 illustrates the behaviour of subjects when attempting to orientate in this scenario. The mean normalized dwell times per ROI indicate that amount of time focused on particular ROIs was not different between the control and intervention groups. The results confirm that the gallbladder was the most important visual cue used for orientation in this scenario followed by the liver and stomach for both groups. Figure 5.2d and 5.2e demonstrate this behaviour and successful use of orientation strategy. Using the gallbladder as an anchor object, relating stomach and liver to deduce orientation was the strategy taught in the tutorial. Conversely, Figure 5.2f illustrates an unsuccessful orientation strategy, with the difference in behaviour confirmed by the position of subject 3 in Figure 5.2h. Examination of the behavioural profiling output graphs in Figure 5.2g-i for the three images of the set suggests that the intervention group adopts a more uniform behaviour compared to the control group. In the output graphs the intervention group is less densely scattered compared to the control group. The intervention group orientated successfully on average in 91% and the control group in 68.9% of images viewed, confirming the relative ease of orientation when faced with an overview of the region. In other words, despite sharing gaze allocation, the intervention group proved to be more aware of the image semantics resulting in an increased orientation performance.

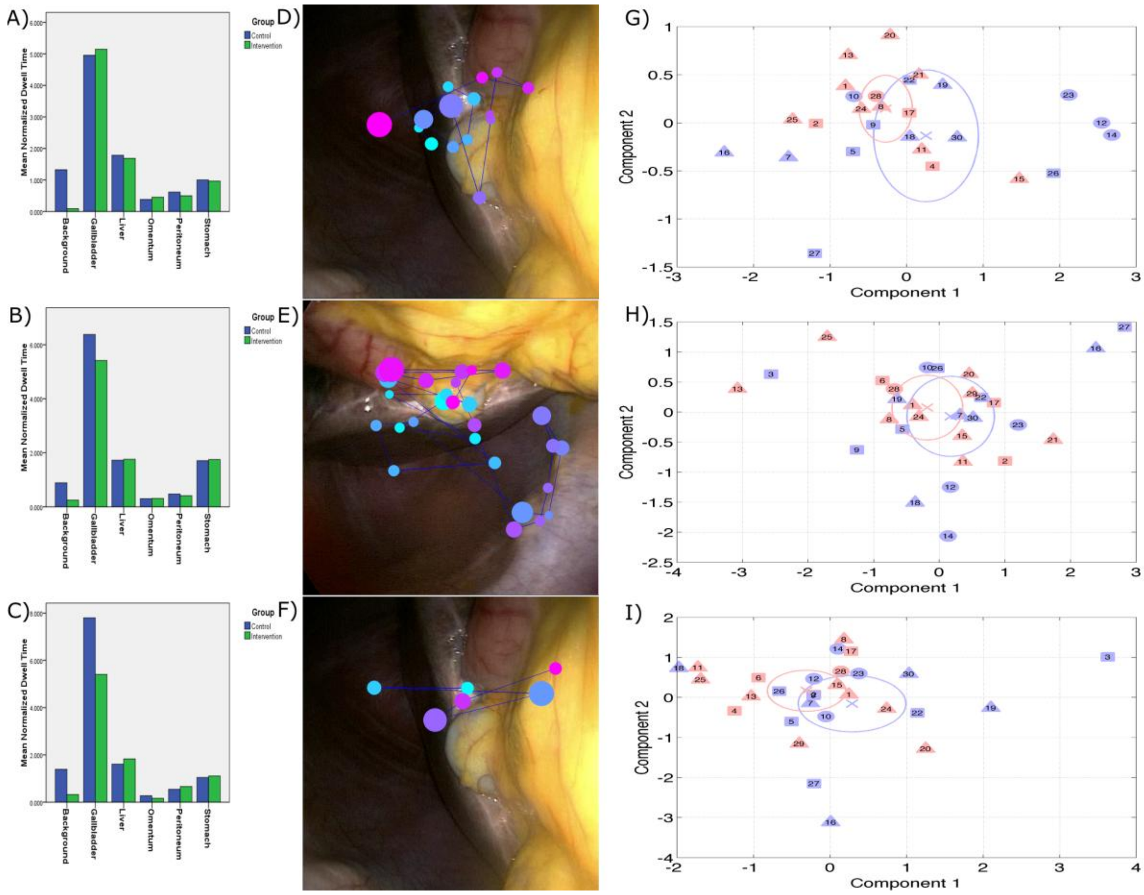


Figure 5.2 Overview of the right upper quadrant **a-c)** Mean normalized dwell times per ROI (ms/pixel2) in stimulus images 2, 5 & 8 respectively **d)** Gaze plot for subject 1 in stimulus image 5 **e)** Gaze plot for subject 1 in stimulus image 2 **f)** Gaze plot for subject 3 stimulus image 5. Gaze plots show earlier fixations (filled circles) coded in blue turning to magenta at the end of the fixation sequence. Area of circle is proportional to dwell time. Saccades are represented by a thin blue line. **g-i)** Behavioural profiling output graphs for image stimuli 2, 5 & 8 respectively. Subjects coded red are intervention and blue control group with shape indicating performance of subject (circle=1-4 correct answers, squares=5-8, triangle=9-12). Subject numbers are indicated within shapes. Coloured cross indicates group average behaviour with sphere representing the average distance from each point in the group to the group average behaviour. The chart axis correspond to the first two (non-linear) uncorrelated variables (i.e. components) explaining maximum variance in decomposing the high-dimensional dataset. Units are arbitrary with component mean centred on 0. Component interpretation is related to the structure under observation.

5.3.3 Close-up of right upper quadrant structures

In this scenario both subject groups paid most attention to the liver and used this as a main reference organ as illustrated in Figure 3a-c. However, substantial differences in their strategy can be established. The intervention group rely less heavily on the anchor as an orientational cue than the control group, freeing fixations to better refer to the relevant peripherals. The importance of the gallbladder and peritoneum as peripherals when determining orientation was confirmed with the intervention group focusing more on these than the control group, which is more in keeping with expert behaviour as taught in the tutorial and illustrated in Chapter 4 by the surgeon subjects. This shift of the attention from anchor to peripherals translates into an apparent separation in behaviour between the two groups. This is clearly illustrated by the intervention subjects grouping more towards the right side of the abscissa axis in the behavioural profiling output graphs. The optimum separation plane [144] between control and intervention is plotted in Figures 5.3g-i) to demonstrate this graphically. The gaze plots of subjects on the right and left of the abscissa axis reveal this difference in behaviour. Subjects on the left side of the graphs focus more on the omentum as an orientational cue and use comparatively fewer other ROIs, compared to those towards the right who use the gallbladder to a greater degree and appear to use a greater number of ROIs to deduce orientation including the peritoneum. This difference is illustrated clearly by the gaze plots of subjects 23 and 28 for image stimulus 4 in Figure 5.3d & e. The gaze plot in Figure 5.3f illustrates well the behaviour taught in the tutorial as described above. This scenario produced a large difference between the groups with the intervention group answering 71.1% and the control group 46.7% of answers correctly and strongly support the hypothesis that orientation skills can be instructed.

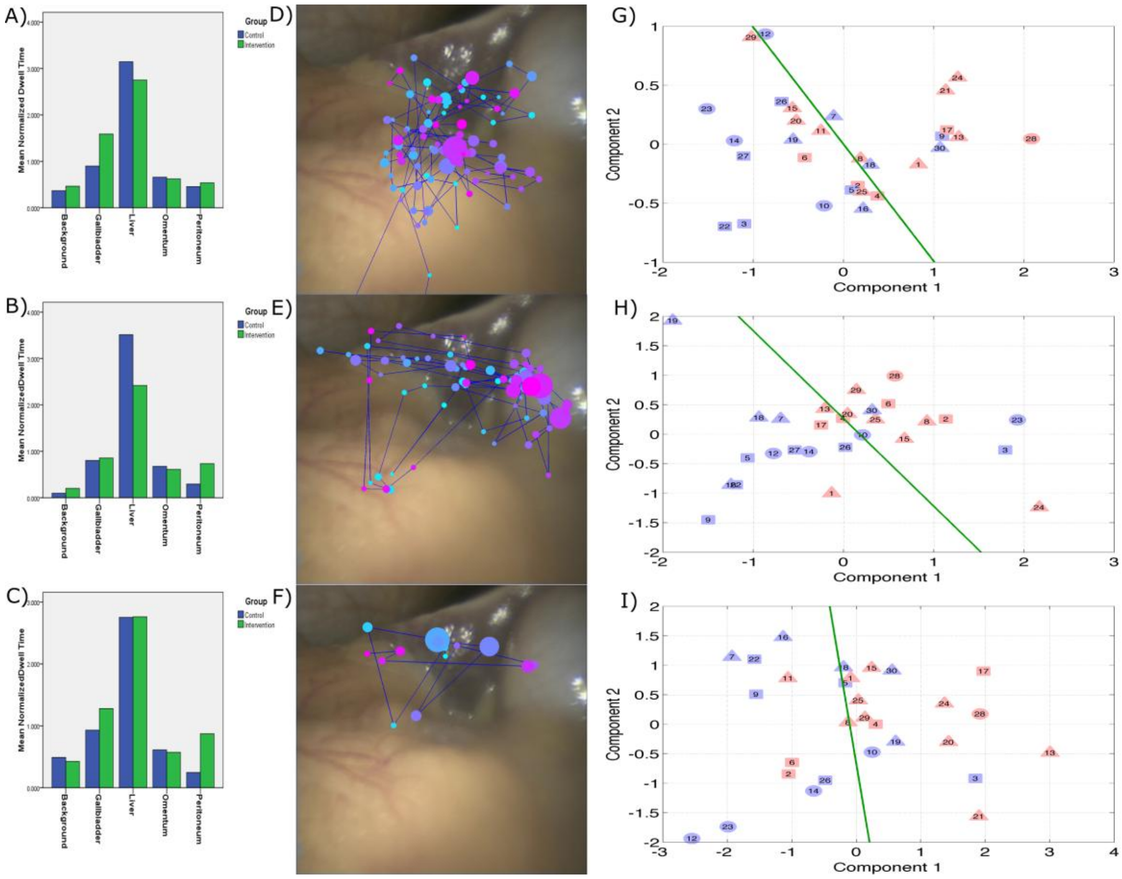


Figure 5.3 Close-up of right upper quadrant structures **a-c)** Mean normalized dwell times per ROI (ms/pixel^2) in stimulus images 4, 9 & 12 respectively **d)** Gaze plot for subject 23 in stimulus image 4 **e)** Gaze plot for subject 28 in stimulus image 4 **f)** Gaze plot for subject 4 in stimulus image 4. **g-i)** Behavioural profiling output graphs for image stimuli 4, 9 & 12 respectively. Coding as for Figure 5.2 Green line indicates the optimal separation plane between intervention and control subjects

5.3.4 Close-up of right upper quadrant structures with gallbladder retracted

When subjects encountered images of this stage of the operation there appeared again to be little difference in the mean normalized dwell time per ROI, with both control and intervention groups focusing heavily on Calot's triangle, gallbladder and stomach as illustrated in Figure 5.4a-c. The intervention and control group orientated an average of 75.6% and 64.4% correctly in this image group, which represents the smallest difference between the groups during all image stages of the operation, but that again can be argued to be due to increased awareness of the image semantics. The relative homogeneity is confirmed by inspecting the visual behaviour output graphs, where there is little difference between the group clusters in Figure 5.4d-f. When viewing the gaze plot of the subject closest to the centre of the intervention cluster (group average behaviour) in all three stimulus images 1, 7 & 10 (Figure 5.4g-i), it can be seen that the orientation strategy used involved identification of the stomach, gallbladder and Calot's triangle and relating the position of the liver to these ROIs, which is the strategy taught in the tutorial.

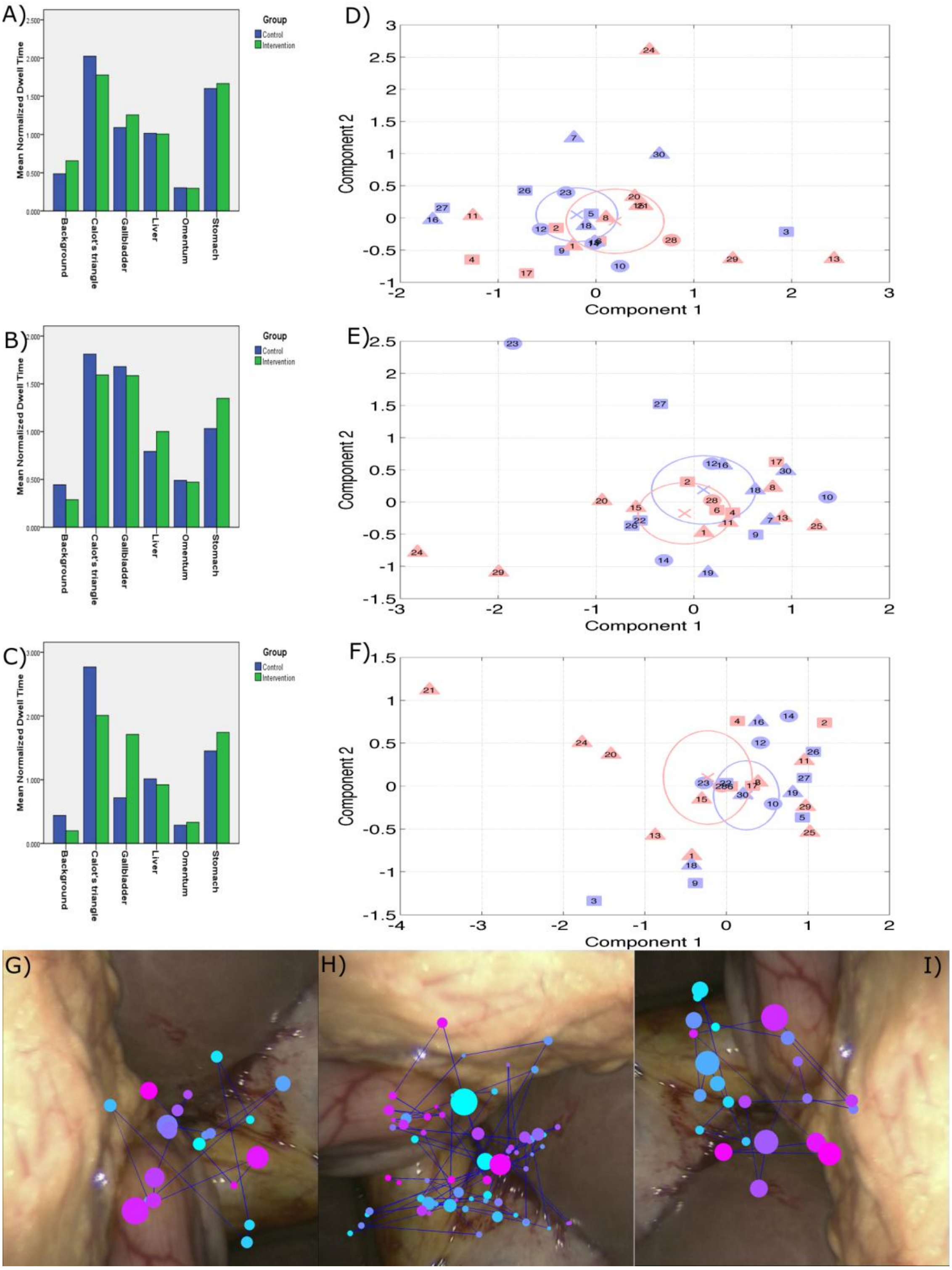


Figure 5.4 Close-up of right upper quadrant structures with gallbladder retracted **a-c)** Normalized dwell times per ROI (ms/pixel^2) in stimulus images 1, 7 & 10 respectively **d-f)** Behavioural profiling output graphs for image stimuli 1, 7 &10 **g)** Gaze plot for subject 20 in stimulus image 1 **h)** Gaze plot for subject 2 in stimulus image 7 **i)** Gaze plot for subject 15 in stimulus image 10. Coding as in Figures 5.2 & 5.3

5.3.5 Dissection of Calot's triangle

A close-up view of Calot's triangle during dissection of the cystic duct was the most difficult scenario to correctly orientate to, illustrated by an average success rate of 64.4% and 44.4% in the intervention and control group respectively. The cystic duct emerges as the anchor object as indicated by the normalized dwell times in Figure 5.5a-c. This is consistent with what was highlighted in the tutorial, but yet again visual behaviour differences separate both groups. The intervention group in particular focused a relatively large amount of attention on the lesser omentum, which is a powerful orientational cue in this scenario as the identification of the cystic duct and lesser omentum alone can determine orientation. Moreover, the intervention group also focus more on the liver than the control group, which provides a dominant clue of whether the image is normal/180° or 90°/270°. The visual behaviour output graphs illustrate obvious differences in behaviour between the two groups as illustrated in Figures 5.5d & 5.5e. It is likely that this difference may be traced back to the training provided. In image stimulus 6, the intervention group heel over to the left of the abscissa axis whereas the control group tilts towards the right. The significance of this can be deduced when examining the individual gaze plots for subject 27 and 28 in Figures 5.5g and 5.5h respectively which show that although both subjects use the cystic duct as an "anchor" object by moving to the left of the abscissa axis (subject 28) a greater amount of attention is placed on either visible side of the liver, the stomach and lesser omentum. The relative positions of these to the cystic duct are instrumental in determining correct orientation. Conversely, subject 27 towards the right of the abscissa axis focuses a lot of attention on the cystic duct and relatively little on the stomach and lesser omentum and does not fixate on one visible side of the liver at all. This makes determining whether the image rotation is normal or 180° difficult.

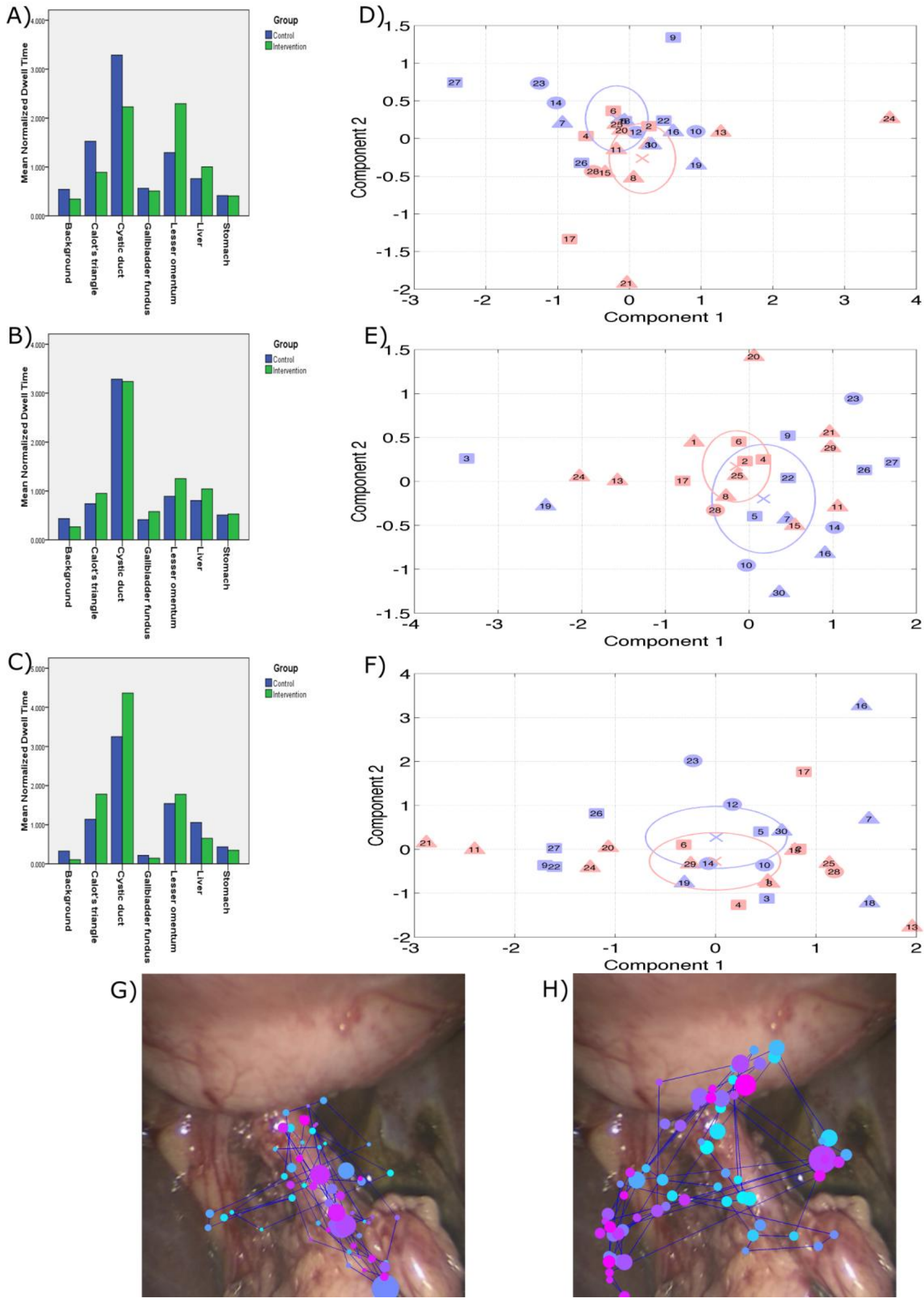


Figure 5.5 Dissection of Calot's triangle **a-c)** Mean normalized dwell times per ROI (ms/pixel^2) in stimulus images 3, 6 & 11 respectively **d-f)** Behavioural profiling output graphs for image stimuli 3, 6 & 11 respectively **g)** Gaze plot for subject 27 in stimulus image 6 **h)** Gaze plot for subject 28 in stimulus image 6. Coding as in Figures 5.2 & 5.3

5.4 Discussion

Having quantified and described high performance orientation strategies at significant stages of a laparoscopic cholecystectomy in Chapter 4, this study represents a natural progression in the investigation of disorientation in the context of this particular operation and MIS.

In this randomized controlled trial of medical students the control and intervention group orientated correctly on average 56.1% and 75.6% of the time respectively. The average orientation rate of all surgeons under identical conditions from the data in Chapter 4 was 78.6%. This suggests that by training novices in successful orientation strategies, their performance in this task can reach the level of a surgeon with several years of experience in laparoscopic surgery. As discussed in the introduction, this does not necessarily mean that novices will make fewer operative errors when disorientated due to the modularity of control systems affecting a final operative decision. It is however intuitive that it will be easier to make the right operative decision under standard on-axis orientation. In addition, by increasing the performance of novices in the orientational process, it is presumed that the cognitive burden placed on them during laparoscopy will decrease. This may increase their ability to learn other essential operative and cognitive skills.

Both groups recognized the importance of key ROIs such as the cystic duct, and focused similar amount of time on these structures, indicating an appropriate basic knowledge of relevant anatomy of the right upper quadrant structures. Differences in behaviour become apparent when viewing the behavioural profiling output graphs. In many cases the intervention group subjects were more tightly clustered indicating more homogenous visual behaviour than subjects in the control group. Also, in several cases the strategies exhibited by the two groups were altogether different, which we argue can be the result of the training, giving the intervention group an advantage in understanding the image semantics. However, in a minority of images, although a difference in performance was apparent, the behavioural profiling output graphs showed no apparent difference between the groups. This suggests that the intervention group performed higher through a greater awareness of image semantics rather than recognition and prioritisation of relevant anatomy at specific stages of the operation. This explanation fits well with the theory of modularity from psychology and enhanced sensory awareness. A 0° laparoscope was used to obtain these images. It is assumed that although the angle from which the image is obtained at a certain stage of the operation may be different with a 30° laparoscope, orientation strategies would not differ provided the same ROI's were present within the scene with appropriate clarity.

Although the subjects showed an increase in performance immediately following the tutorial, it is not known how much will be retained long-term. Although this paradigm has never been investigated in relation to orientation, it has however been shown that for education in cognitive skills involved in surgical decision making in trauma the impact is durable and cognitive skills persist at least 6 months after the educational event [145]. Another issue is the duration of the training. Although this experiment investigated specific orientation strategies at determined stages of a particular operation, performance may have increased even further after a more exhaustive tutorial followed by targeted training. It has been shown though for skills such as cardiopulmonary resuscitation, that the effectiveness of a short tutorial can be as successful as multi-hour courses with similar retention of skills at 6 months [146]. The results suggest that if skill training in disorientation is to be successfully integrated into a surgical curriculum, tutorials for specific operations need to be brief and succinct such as the one used in this experiment.

The results presented in this chapter indicate that orientation training should form part of the basic laparoscopic curriculum of surgical training, and it is expected that this training will shorten the learning curve associated with orientational skills. A proportion of experienced surgeons who consistently perform below average will potentially benefit from this training. However some may be at the limit of their innate potential and this assessment paradigm may serve as a test to discriminate those surgeons who have a limited capacity to learn orientation skills. An interesting application of this would therefore be in the assessment of poorly performing surgeons to differentiate those who may be best advised to not perform certain laparoscopic procedures due to an increasingly high risk of disorientation and therefore patient harm due to their innate abilities compared with those who would benefit from targeted training.

Furthermore, the impact of gaining or improving this skill set will be applicable to novel scenarios such as other laparoscopic operations, and should also facilitate orientation in unusual or unexpected scenarios such as in cases where diseased tissue or abnormal anatomy is encountered. In an era of rapid technological innovation this is an area of surgical research which deserves significantly more resource allocation, comparable to that of the aerospace and military industries, which similarly rely on humans operating complex computer-assisted systems using vision as the main sensory input.

In this chapter, it has been shown that orientation performance in medical students with a basic knowledge of anatomy increases after training in this prospective randomized controlled trial. In future work it would be interesting to examine if acquisition of operative or other cognitive skills associated with laparoscopy increases in subjects who have a relatively lighter cognitive load compared to those who had not undertaken training in orientation. For educational purposes, in a laparoscopic curriculum it is clear that high performance orientation strategies need to be quantified and described for other common laparoscopic operations that contain critical stages associated with significant morbidity due to operator disorientation. In an optimally constructed laparoscopic training curriculum, orientation training should be combined with psychomotor skills training in a procedure-specific syllabus. It is also of great importance to evaluate orientation in other areas of MIS which may be associated with an even higher risk of operator disorientation, such as NOTES.

Chapter 6 Orientation strategies in Natural Orifice Translumenal Endoscopic Surgery

This chapter is based on a study published in Annals of Surgery and presented at the Association of Laparoscopic Surgeons of Great Britain & Ireland Annual Scientific Meeting, Nottingham, 25 – 26 November 2010 as referenced in introductory chapter.

6.1 Introduction

In Chapter 5, one particular beneficial application of quantifying orientation strategies has been demonstrated, in the context of improving performance through education of specific behavioural patterns. Subsequently it is important to identify other appropriate niches within MIS which may benefit from further evaluation using this framework as well as additional applications of this data which may decrease disorientation. As discussed in Chapter 2, NOTES represents the latest drive in MIS to further decrease morbidity and hospital length of stay compared to laparoscopic surgery by eliminating abdominal wall incisions. NOSCAR identified disorientation as one of the key issues to be resolved prior to widespread clinical implementation of NOTES [105]. Other important challenges identified included a lack of multi-tasking, instrument triangulation, ability to suture and perform safe anastomoses (see Table 2.1).

Despite sharing with laparoscopic surgery a two-dimensional monitor as the visual interface, several factors have been outlined in this thesis which make NOTES operators even more prone to disorientation than traditional laparoscopists. These are almost exclusively related to the conventional flexible endoscope. In addition to disorientating factors known in laparoscopy, the NOTES surgeon does not have a cue outside the body indicating the position of the camera on the inside and the endoscope is much more prone to rotational movements than the laparoscope. Furthermore, the flexible endoscope, originally designed for intralumenal use, is an ergonomically challenging tool to operate due to its limited control mechanism and the operator frequently has to manipulate instruments coming out of the endoscope along the same axis. Images viewed through the endoscope during NOTES are likely to divert from standard laparoscopic views. The endoscope is often in a retroflexed position and therefore the image may be upside down. Moreover the endoscope often lies on structures supporting it thereby partially obscuring the view. Evidence suggests that even in the orientated state, performance is optimum in the traditional horizontal view [147].

Despite the increased number of disorientating factors associated with NOTES, it is hypothesised that in line with previous findings in laparoscopic cholecystectomy in Chapter 4 there will be certain behavioural strategies associated with high performance. In addition, we aim to further disclose structures relevant to NOTES surgeons during the re-orientation process. With superior experience using the flexible endoscope gastroenterologists and interventional endoscopists provide a complimentary skill-set to surgeons in NOTES procedures, however the majority of early NOTES trials have been carried out by surgeons [148]. With less experience in operative anatomy and laparoscopy, gastroenterologists are likely to be even more affected by disorientation.

Since NOTES is still a concept in evolution, there is a significant gap in our understanding regarding disorientation within this environment. Understanding effective re-orientation in NOTES is of great importance. By understanding the importance of individual cues and visual relationships, it may be possible to 1) teach successful re-orientation strategies to novice or under-performing operators, and 2) guide new NOTES platforms designs to decrease disorientation.

Saliency refers to the perceptual quality by which objects or features in an image or scene stand out from the rest [149]. In the absence of deliberate focus, visual attention is guided towards salient features [149,150]. The mechanisms by which saliency influences attention have been established previously [151-153]. NOTES surgeons should be able to apply their knowledge of anatomy to guide their orientation efforts during the procedures but due to novelty of the landscape, it is unlikely to be as effective as during conventional laparoscopic procedures. As has been performed in previous chapters, visual behaviour will be captured using eye tracking to discern a surgeon's point of gaze throughout the entire orientation process and then expressed in terms of eye movements. Fixation dwell times surrogate presumed attention focus on the fixated object. If we were to unveil the fundamental anatomical features involved in orientation processes, these dwell times must be normalized by the area occupied by organ in the image and its associated saliency.

The hypotheses to be tested in this study were:

1) that visual attention strategies employed by surgeons which are associated with high performance in reorientation during specific NOTES scenarios can be described, and
2) that key structures guiding attention deployment of the surgeon in the process of self-orientation in common clinical NOTES scenarios can be identified

6.2 Methods

6.2.1 Subjects & Experimental design

Following approval by the Institutional Review Board (IRB) 21 surgeons with no previous NOTES experience were recruited (19M: 2F). Mean age was 31.6 yrs (range 28 – 38 yrs). There were 4 consultant, 3 senior registrars and 14 junior registrars. Subjects provided appropriate prior consent and were shown 8 images acquired during human NOTES operations from the flexible endoscope from both usual and unusual viewpoints so to induce disorientation. Visual behaviour was recorded as the subjects were asked to establish orientation.

Subjects were asked to assess: 1) the configuration of the flexible endoscope within the peritoneal cavity, 2) the image orientation (the images can only have been manipulated on a rotational axis in increments of 90° from a "normal" view), and 3) the orifice used to access the peritoneal cavity. Subjects were provided with a sample picture and correct answer and informed that the anatomy in each image was normal and at one time there was only one flexible endoscope present in the peritoneal cavity.

For a subject to be fully orientated all 3 questions above would have to be answered correctly. Each answer was awarded a binary correct/incorrect therefore giving a maximum total orientation score of 3 for each image and 24 across the 8 image set. No time limit was imposed to provide an answer for each image. Subjects controlled the progression of images using a keyboard and recorded answers on a sheet provided. Subjects were not told if their answers were correct.

6.2.2 Image stimuli

The stimuli used for this experiment are illustrated in Figure 6.1. Three image groups corresponding to common NOTES scenarios [148] contain the same images under various rotational transformations:

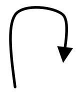
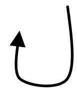
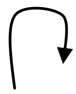
1) Retroflexion from transvaginal access to view pelvic organs

2) Retroflexion from transgastric access to view right upper quadrant organs, and

3) View of right upper quadrant organs from a pelvic access.

Each image or stimulus was manually segmented into regions of interest (ROIs) delimiting the different significant organs, structures and instruments. We acknowledge that this may result in minimal errors in determining the boundaries; however we have considered this negligible in biasing our findings. Defined ROIs of each image and their rotational orientation, access route and endoscopic configuration are given in Table 6.1.

Table 6.1 Image groups used during the experiment with relevant identified regions of interest and orientation

Image Groups	Regions of Interest	Orientation of Image	Access route	Configuration of endoscope
1		Normal		
5	Peritoneum, Falciform ligament, Omentum, Liver	90° clockwise	Pelvic	
2		180°		
4	Endoscope, Uterus, Broad Ligament, Vaginal vault, Trocar, Ovary, Colon, Omentum, Peritoneum	90° anticlockwise	TV	
7		90° clockwise		
3		Normal		
8	Liver, Stomach, Endoscope, Peritoneum, Omentum	180°	TG	
6	Uterus, Broad ligament, Trocar, Endoscope, Peritoneum, Omentum	Normal	TV	

TV=transvaginal TG=transgastric

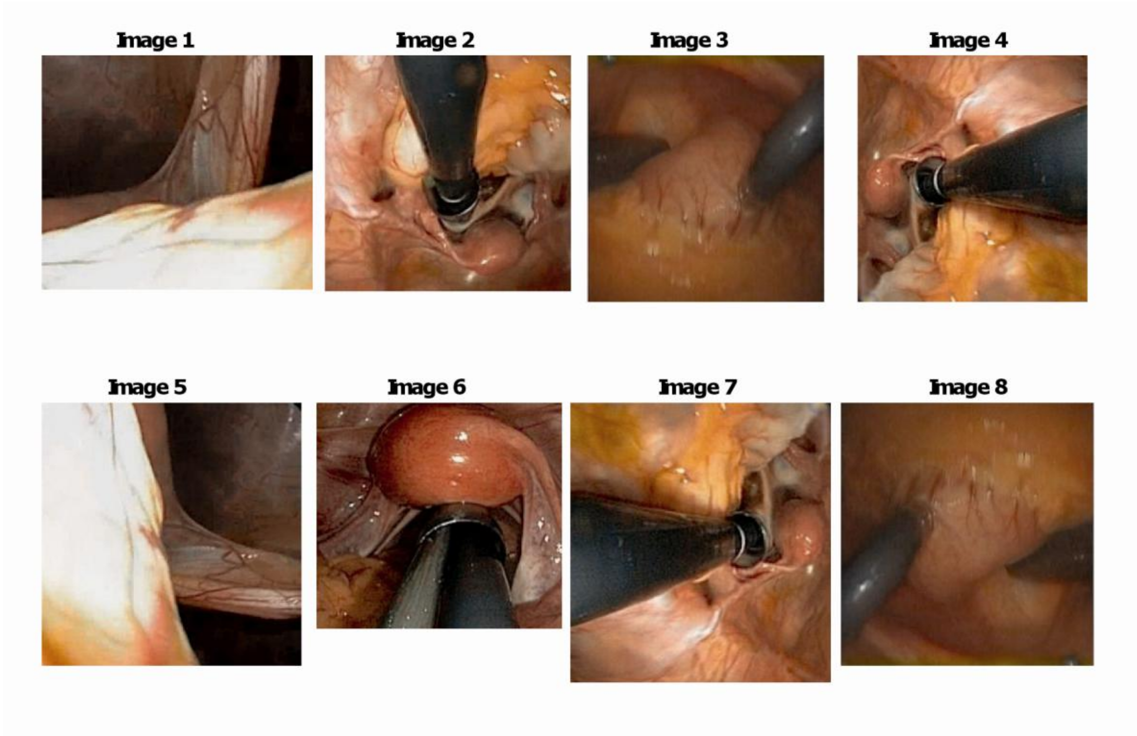


Figure 6.1 Images used as stimuli during the experiment.

6.2.3 Eye-tracking

Eye gaze was tracked using an binocular eye-tracking system (Tobii ET 1750, Tobii Inc, Sweden) at 30 Hz as used in previous experimental chapters. Pupil and corneal reflections (known as Purkinje reflections) from infrared light beamed at the subject's eye are used to establish gaze location at the screen plane within 1 degree of accuracy. Fixations corresponds to when the gaze does not move further than a hard threshold (30 pixels), during a minimum of a 100ms [29].

6.2.4 Analysis framework

The analysis aims to:

1) Describe and quantify the most representative successful orientation strategy for each NOTES scenario
2) Determine the importance of various organs and structures in each scenario when natural scene saliency has been compensated for.

Time taken to establish orientation, eye tracking parameters, and fixation sequences on ROIs were recorded. Specific orientation strategies were quantified using the algorithm validated for comparing visual reorientation behaviour for bench top simulations and laparoscopic cholecystectomy used in Chapters 3 & 4. Briefly, fixation sequences are captured as single points on a two-dimensional chart. Proximity among points in this chart results from sequences similarity, thus enabling comparisons in orientation behaviour. Furthermore, the point location along the X axes relates to a structure recurrently focused on, referred to as an “anchor”. By examining the gaze plots of individual subjects, orientation strategies can be quantified. Subjects were grouped according to their performance. For the highest performance group (total orientation scores of 22-24/24; n=9/21), the subject closest to the group centroid was selected as the most representative to discern the archetypal successful reorientation strategy. Image salience was established using local changes in contrast with higher salience assigned to less frequent contrast patterns[154]. Fixation maps represent the spatial distribution of fixations over the image. Foveal vision extends beyond the fixation point. Accounting for foveal vision yields gaze maps capturing the spatial distribution over the visual field. These are later compensated with the image saliency. Saliency normalised dwell time per ROI then identify those elements relevant to surgeons beyond the naturally salient features. Figure 6.2 summarises the approach for deriving normalised dwell time.

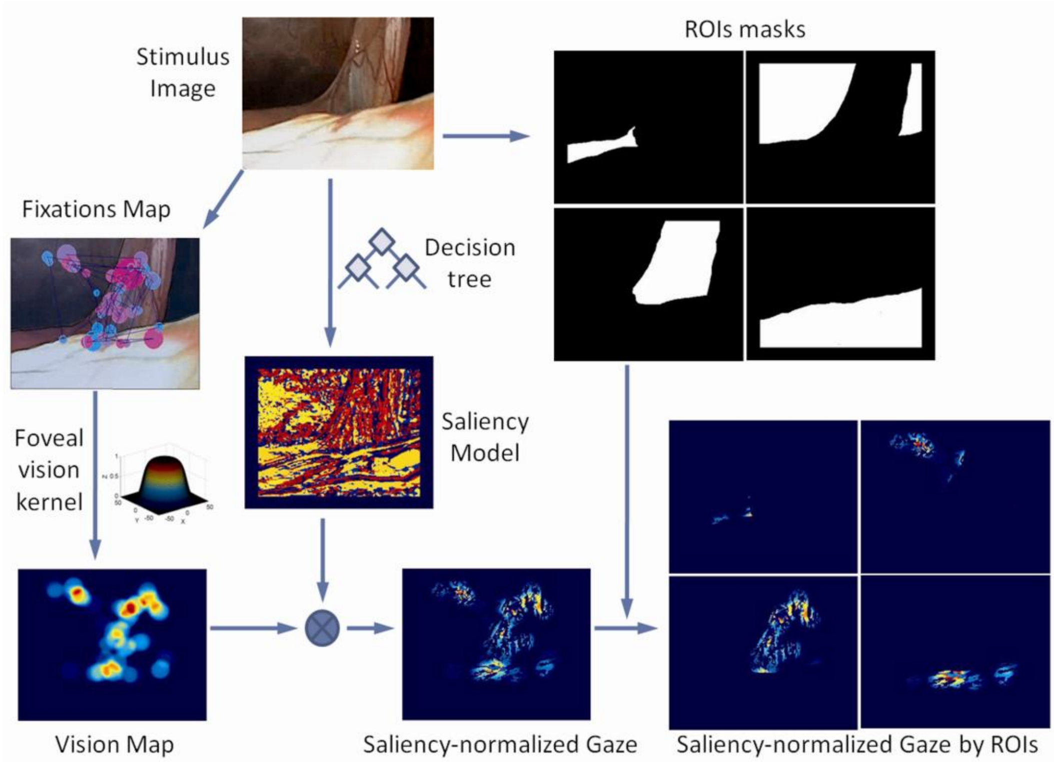


Figure 6.2 Schematic data analysis approach. Fixation locations are mapped to manually segmented ROIs over the stimulus image. Gaze dwelling times in each ROI are derived from the vision map already accounting for foveal vision and corrected for scene natural salience.

6.2.5 Statistics

Comparisons between groups of non parametric variables were done using the Kruskal-Wallis test and parametric variables were done using ANOVA with Bonferroni correction. Individual variables were compared using the Mann Whitney U test or the Student *t*-test as necessary. Correlations of continuous variables were determined by nonparametric linear regression. Statistical analyses were performed using SPSS v16.0 (Chicago, USA). Differences were considered statistically significant at $p<0.05$.

6.3 Results

6.3.1 Performance: Orientation scores

Subjects had a mean laparoscopic experience of 116 operations as primary operator and 365 operations as first assistant. There was a significant positive correlation between laparoscopic experience as primary operator (p=0.011; r_s =0.541) and total orientation score however there was no correlation between laparoscopic experience as assistant (p=0.196; r_s =0.294) and total orientation score. Orientation scores jibed with seniority as shown in Table 6.2 although this did not reach statistical significance. There were no significant differences in time taken to orientate or mean number of fixations between seniority groups. There was a tendency for consultants to spend less absolute dwell time per ROI, but upon area and saliency correction this was not significant as illustrated in Table 6.3.

Table 6.2 Mean scores of correct answers per subject seniority group

	Configuration of Endoscope (/8)	**Orientation of Image (/8)**	**Orifice used for Access (/8)**	**Total orientation score (/24)**
Junior Residents	6.1	6.8	5.4	18.3
Senior Residents	6.7	7.7	6.7	21
Attendings	7.8	7.3	7	22
P	0.438	0.59	0.23	0.312

Table 6.3 Comparison of basic eye tracker parameters by seniority of subject

	Junior Residents	**Senior Residents**	**Attendings**	**P**
Mean time taken to answer (sec)	23.9	31.5	22.9	0.076
Mean number of fixations	45.8	46	44.5	0.884
Mean absolute dwell time / ROI (ms)	3122	2116	1936	0.005
Mean normalised dwell time (ms/pix^2/-)	17331	13547	17495	0.186

Subjects irrespective of seniority were divided up into 3 performance groups according to their total orientation score (<18=low n=4; 18-21=medium n=8; 22-24=high n=9). As seen in Table 6.4 high performance subjects tended to take less time to orientate using fewer fixations, spending less dwell time per ROI, even after normalization for area and saliency, thus evincing a more specific and focused approach to orientation compared to those who performed poorly.

Table 6.4 Comparison of basic eye tracker parameters by performance of subject

Performance	Low	Medium	High	P
Mean time taken to answer (sec)	24.5	25.7	19.9	0.145
Mean number of fixations	49.5	61.5	29.6	<0.005
Mean absolute dwell time / ROI (ms)	1976	2638	1114	<0.005
Mean normalised dwell time (ms/pix^2/-)	20051	18223	14142	0.004

6.3.1.1 Limited view of right upper quadrant structures through pelvic access (Images 1 & 5)

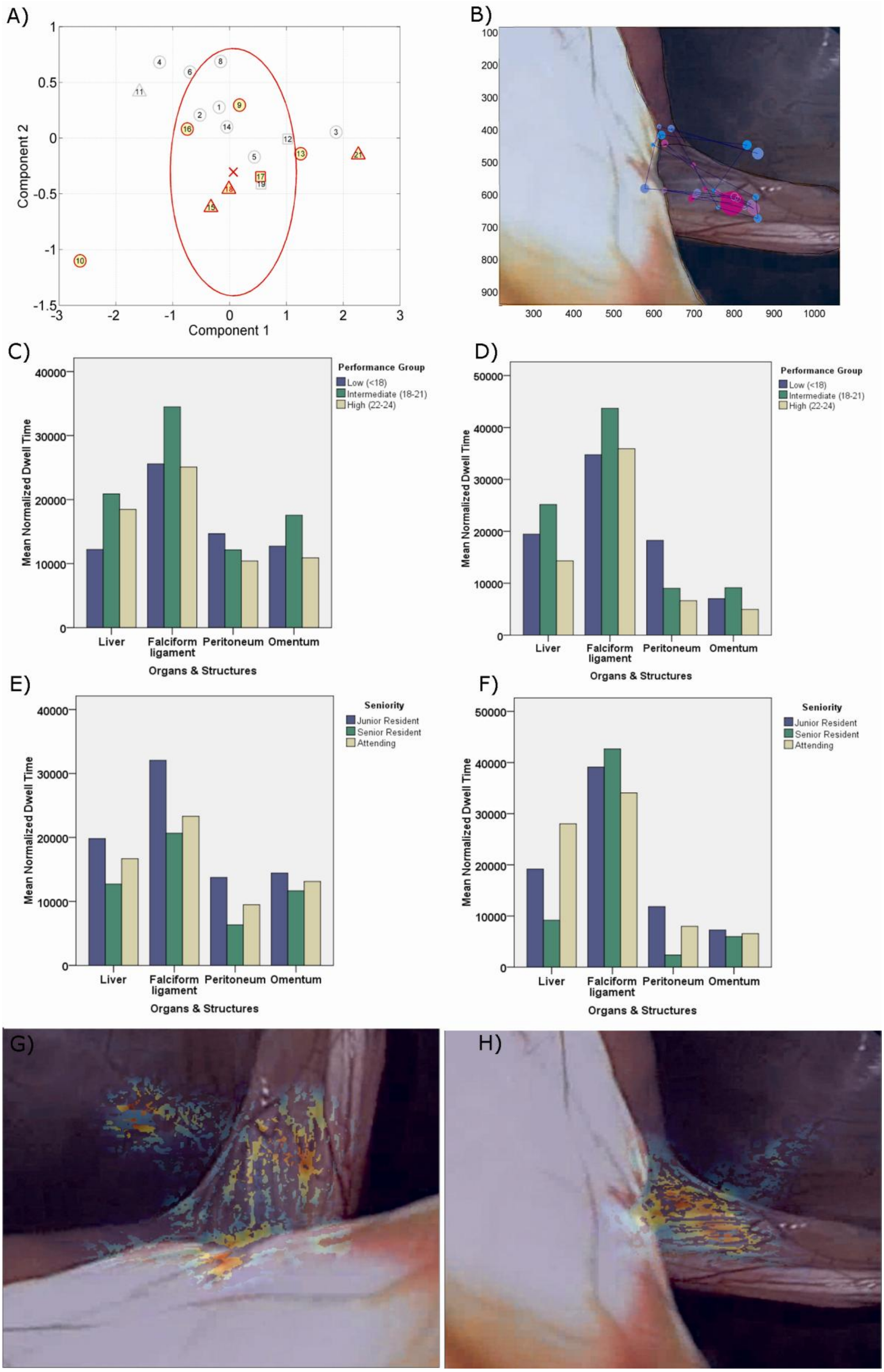
The popularity and relative safety of the transvaginal access route [155] and the fact that cholecystectomy has been the most commonly performed NOTES procedure [148], makes this a common view during NOTES trials. The view to the right upper quadrant is likely to be obscured by omentum or bowel as the endoscope rests on these structures during navigation.

As revealed for laparoscopic cholecystectomy in Chapter 4, differences between performance groups can be explained on the basis of the orientation strategy. Figure 6.3a shows the visualisation sequence output for the high performance subjects. The gaze plot in Figure 6.3b corresponding to the group's most representative subject, chosen as explained in the methods, exposes the successful orientation strategy. This consists of using the falciform ligament as anchor and subsequently relating this to the liver, omentum and peritoneum of the abdominal wall. In general, as will be confirmed in other scenarios, following identification of an anchor organ subsequent fixations on remaining structures referred to as peripheral are related back to the anchor for successful orientation. Note peripheral is used without connotation of the structure location in the image.

Normalized dwell times on the various organs in Figures 6.2c-f were similar across seniority and performance groups suggesting similar amounts of attention placed on individual organs across the cohort. In other words, the structures relevant to surgeons transcend the sequence in which they are attended and thus the orientation strategy. This was a consistent finding across all scenarios. Therefore, for subsequent images the normalized dwell times are illustrated as means across all subjects. Of course, identification of such structures relevant for orientation in NOTES still remains.

The saliency-normalized vision maps averaged across high performing subjects in Figures 6.2g and 6.2h illustrate the key areas focused on by subjects who performed highly during the re-orientation process and their exact location on the organs of interest. For this view, the falciform ligament represents the most important visual cue in this scenario, followed by the liver despite being partially occluded and then in relatively equal proportions the omentum and peritoneum.

In the remaining scenarios we proceed to describe the results in the same way; by first describing a prototypal successful orientation strategy and then describing the weight posed on the different organs and structures by the surgeons.



A)
Component 1
Component 2
B)
C)
Performance Group
Low (<18)
Intermediate (18-21)
High (22-24)
Mean Normalized Dwell Time
Liver
Falciform ligament
Peritoneum
Omentum
Organs & Structures
D)
E)
Seniority
Junior Resident
Senior Resident
Attending
F)
G)
H)

Figure 6.3 a) Output of visual path algorithm with centroids calculated by k-means algorithm (illustrated by cross in the middle of sphere) for subjects in the high performance group (22-24 correct total orientation score – coded in red) for stimulus image 5. Closest subject identified by highlighting number red. **b)** the gaze plot with initial fixations coded in blue turning to red to the end of the sequence. Size of circle indicates fixation duration. **c&d)** mean normalized dwell times by performance for stimulus images 1 and 5 respectively, **e&f)** mean normalized dwell times by seniority for stimulus images 1 and 5 respectively, **g&h)** averaged saliency-normalised vision maps of high performance subjects for stimulus image 1 and 5 respectively.

6.3.1.2 View of pelvic organs with retroflexed endoscope from transvaginal access – (Images 2, 4 & 7)

Pelvic organs can be accessed for relatively simple procedures such as ovarian cystectomy [94], making this a common NOTES scenario.

In this case the trocar acts as anchor whilst vaginal vault, uterus and endoscope are chosen as peripherals. This more common strategy is by no means the only successful. For instance, subject 9 in Figure 6.4a uses the endoscope as an anchor object (gaze plot not shown), but still successfully reorienting himself. This unique strategy is illustrated as a point away from the rest on the output graph.

The identical distribution of normalized dwell times in Figures 6.4c, 6.4d and 6.4e confirms the consistent approach in identifying important organs and structures for orientation. The specific key areas that high performance subjects focused on during the re-orientation process for each image are illustrated in Figures 6.4e, 6.4f and 6.4g. Unsurprisingly, the trocar represents the most important visual stimulus for orientation, with high amounts of attention paid to several nearby organs including the vaginal vault, the uterus and the broad ligament. This makes sense because not only is the trocar the obvious structure to examine to determine access organ, but when considering the individual geometry and anatomical position and relation to the access point of these structures they provide strong visual clues to image orientation.

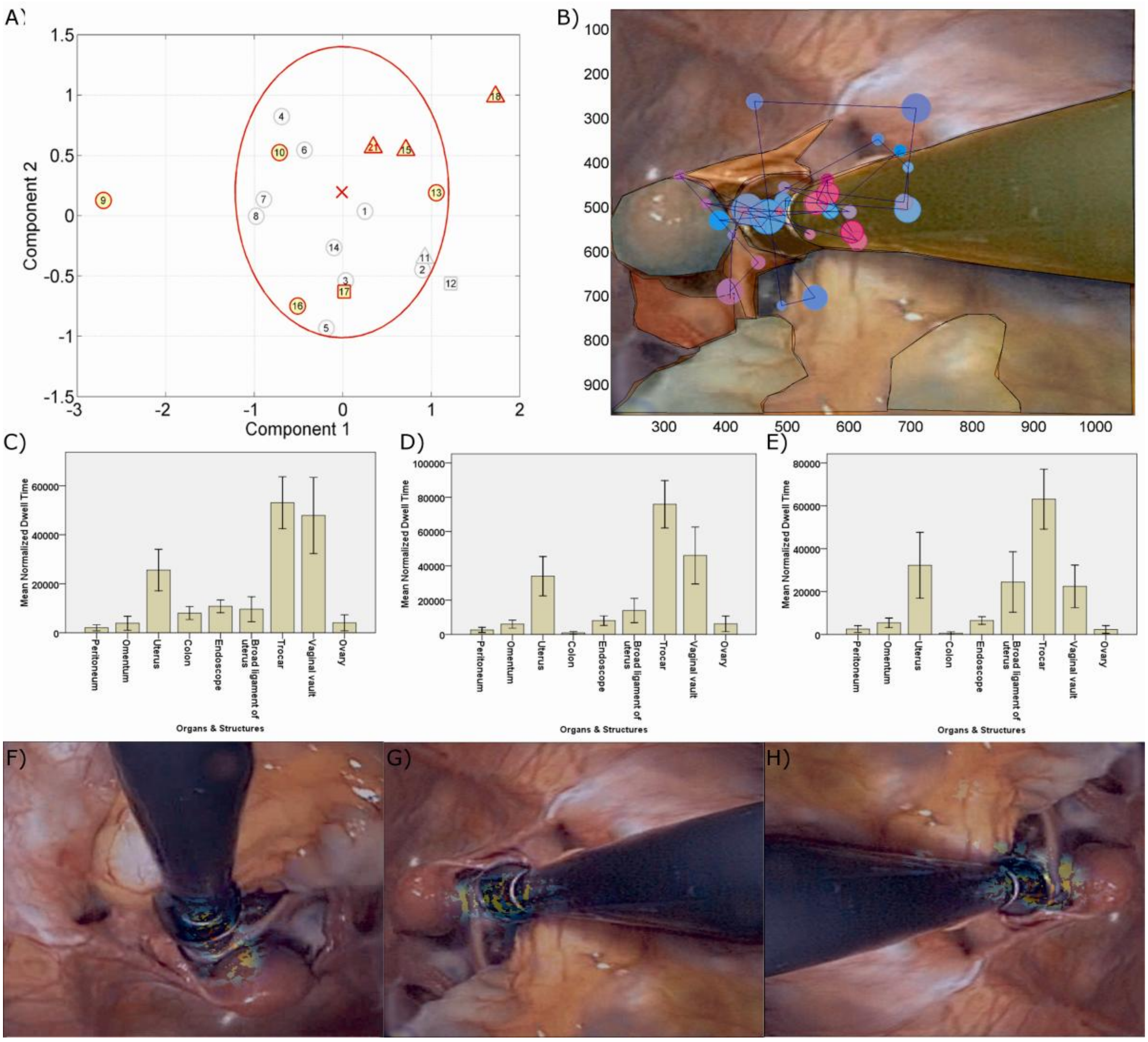


Figure 6.4 a) Output of visual path algorithm for stimulus image 4, **b)** Gaze plot of closest subject to high performance centroid, coding is as for Figure 3. **c,d&e)** mean normalized dwell times across all subjects in stimulus image 2, 4 & 7 respectively. Error bars indicate 95% CI. **f,g&h)** averaged saliency-normalised vision maps of high performance subjects for stimulus images 2, 4 & 7 respectively. The saliency-normalized vision maps therefore illustrate the regions of greatest importance within the image in the process of orientation despite the area or saliency of the particular ROI that the gaze is focused on

6.3.1.3 View of right upper quadrant structures from retroflexed transgastric access – (Images 3 & 8)

As the transvaginal approach is only available in half the population and with doubts about the universal acceptance [103], particularly in younger women, transgastric access is expected to be of interest in NOTES research as it has proved to be in patient surveys [156].

Figures 6.5a and 6.5b presents the stomach as the scenario anchor object and the endoscope as the main supportive peripheral structure. Of course, it is necessary to relate other peripheral structures such as the liver and peritoneum to these to determine orientation and as is apparent in Figure 6.5b many fixations are placed in the border regions between the stomach and other ROIs.

In agreement with the other scenarios the anchor object receives the largest dwelling time even after accounting for saliency. As can be seen from Figures 6.5c and 6.5d, the stomach was by far the most attended visual cue during orientation. This is likely to be because it is the organ through which the access route is established but also due to the anatomical location, as it provides strong relational cues between itself and the liver and peritoneum. Of the peripheral structures, the endoscope was perceived as an important visual cue suggesting that it was necessary to relate the position of the tool with regard to the anatomy. When inspecting the saliency-normalized visual map of high performance subjects in Figures 6.5e and 6.5f in more detail, specific areas of the stomach close to both the liver and endoscope are pinpointed as key areas for attention focus.

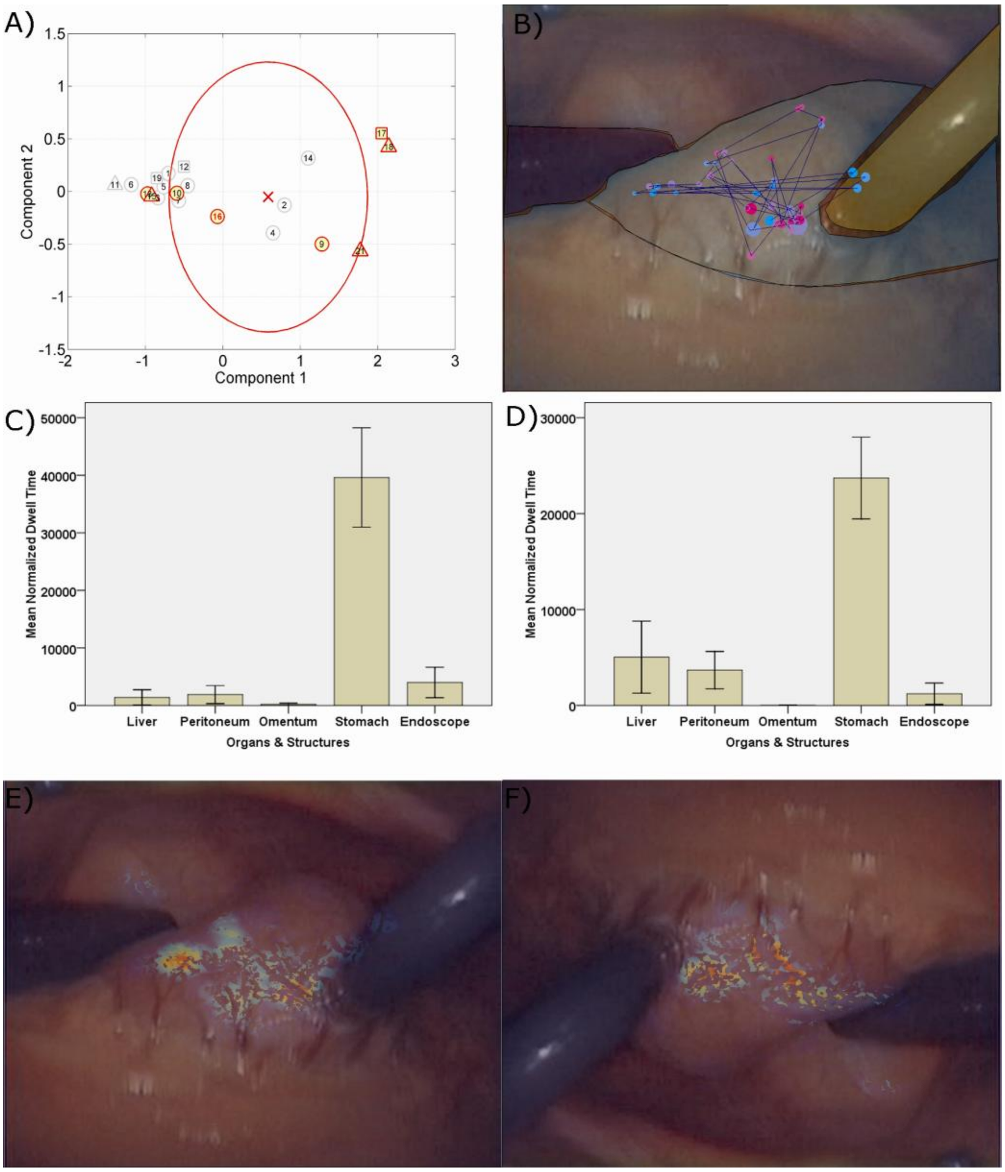


Figure 6.5 a & b) Output of visual path algorithm and gaze plot for subjects in high performance group closest to centroid for stimulus image 8. Coding is as for Figure 6.3. **c&d)** mean normalized dwell times across all subjects in stimulus images 3 & 8 respectively. Error bars indicate 95% CI. **e&f)** averaged saliency-normalised vision maps of high performance subjects for stimulus images 3 & 8

6.3.1.4 Close-up view of pelvic structures from retroflexed transvaginal access – (Image 6)

This is a close-up image of the transvaginal access point viewing the female pelvic organs in close proximity. The successful orientation strategy adopted by subject 17 in Figure 6.6a becomes clear when inspecting the gaze plot in Figure 6.6b. The anchor structure is the trocar, which is referred back from the peripherals of endoscope, uterus and broad ligament. Subject 20 only used 2 fixations to establish orientation, one on each side of the broad ligament of the uterus (gaze plot not shown).

Figure 6.6c again confirms the importance of the trocar to determine the access organ and relative rotational orientation. Other organs and structures appear to be used in equal proportions with the endoscope receiving slightly more attention as orientation was established. In combination with the view of the pelvic organs from transvaginal access, this scenario accentuates the importance of external (non anatomical) objects as key for reorientation. In particular Figure 6.6d highlights the relatively small area of the image receiving the vast majority of visual focus.

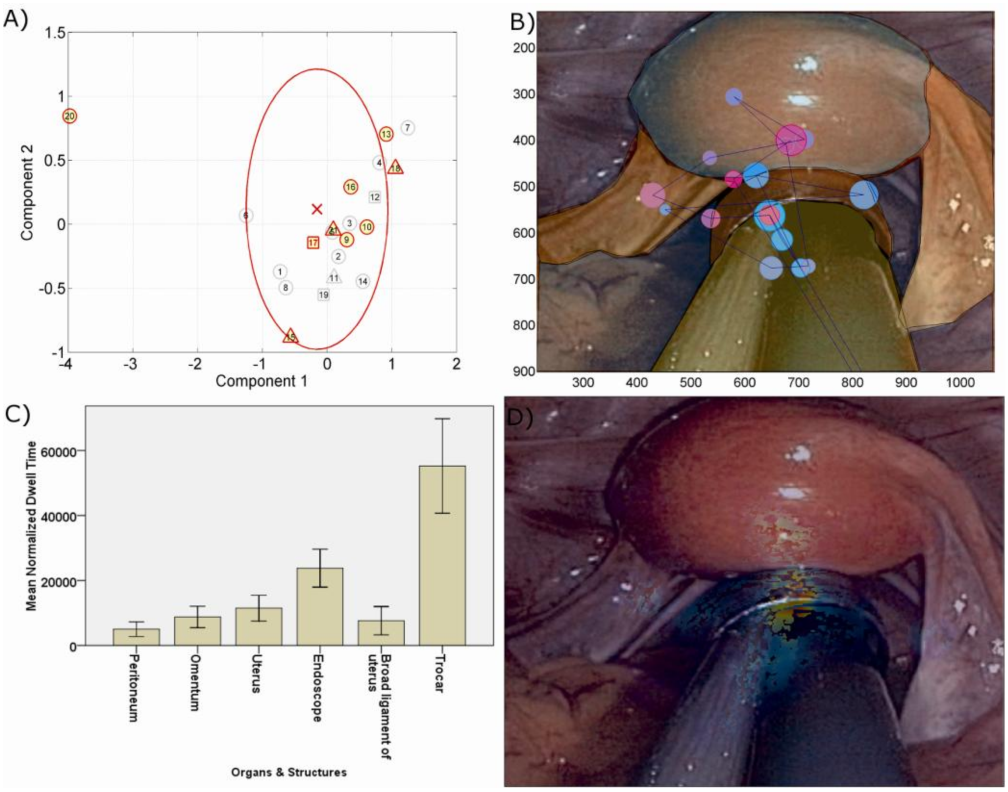


Figure 6.6 a & b) Output of visual path algorithm and gaze plot for subjects in high performance group closest to centroid for stimulus image 6. Coding is as for Figure 6.3. **c)** mean normalized dwell times across all subjects in stimulus image 6. Error bars indicate 95% CI, **d)** averaged saliency-normalised vision map of high performance subjects for stimulus image

6.4 Discussion

By quantifying successful orientation strategies for specific scenarios and identifying the most important visual cues in a similar fashion to the laparoscopic cholecystectomy study in Chapter 4, this experiment represents the first step in understanding disorientation in NOTES. These operations introduce not only novel visual landscapes not normally seen in laparoscopy but also a new set of visual cues, such as the operating endoscope and trocar when viewed in retroflexion. The importance of these visual cues in relation to orientation is previously undetermined. We chose to investigate surgeon specialist subjects as it was presumed they would perform higher in the re-orientation process because of previous knowledge of laparoscopy but the results are highly applicable to the gastroenterologist undertaking NOTES.

High performance subjects had a lower number of fixations and normalized dwell time per ROI compared to the other performance groups, suggesting a more structured and focused approach to orientation, similar to the pattern unveiled in Chapter 3. Seniority groups did not differ in performance or the time taken to orientate to each image however there was a significant correlation between laparoscopic experience as primary operator and total orientation score. Whilst higher subject numbers may reveal behavioural differences, the focus of this study was to outline important visual cues and to describe successful orientation strategies, rather than to establish proficiency differences. Similarly, it is recognized that interesting implications could be drawn in comparing subjects with specialized characteristics such as familiarity with an unstable horizon or with significant NOTES experience, which represents an avenue for further investigation.

In assessing the significance of a fixation placed on a ROI, in addition to the area occupied by that ROI, in this experiment the saliency of the ROI was considered in the normalization process of the dwell time data. Due to the novel views and additional features (such as a trocar or the endoscope in a retroflexed position) present during NOTES operations, it was felt that most meaningful conclusions would be drawn if both ROI area and saliency were accounted for in evaluating the significance of a particular fixation during orientation. This also allowed for representation of this data graphically in saliency-normalized visual maps, which were considered to be more important for NOTES than in the analysis performed for laparoscopic cholecystectomy in Chapter 4, due to the potential applications of disorientation tools in computer-assisted and NOTES-specific operating platforms.

Another important consideration in this study design and that used in Chapter 4 was whether to analyze static or dynamic images, recognizing that particularly in flexible endoscopy position recognition is influenced by the way the endoscope responds to controls or reacts with advancement or withdrawal. It is recognized that individual endoscopists use specific endoscope manoeuvres in position recognition, which would not be universally represented in a video, nor would the subject be able to determine what endoscope movement resulted in the view observed in the video. Therefore for most meaningful data acquisition the subject should retain individual control of the view during orientation. This would require in-vivo manipulation of the endoscope starting at the disorientating image, and it was concluded that this experimental protocol in a human patient would be unethical. Furthermore, because of a lack counter-forces imposed by the lumen of GI tract and potential configuration of endoscope (i.e. often in retroflexion) translation of the flexible endoscope in NOTES procedures will often result in undesired movement of the endoscope tip. Therefore, as in laparoscopy, it may be appropriate to limit advancement or withdrawal of the endoscope during surgical NOTES procedures, thereby limiting the use of dynamic images in orientation.

The fact that normalized dwell times per ROI are similar across images in the same set supports the idea that subjects use a consistent and comparable reorientation strategy when faced with analogous conditions. This is consistent with both animal[57] and human studies[59] in the psychology literature. The importance of an anchor object to establish orientation as previously revealed in stages of laparoscopic cholecystectomy in Chapter 4 was again confirmed in this experiment as a powerful successful orientation strategy. Anchor-structure based orientation strategy as deduced from the high performance group’s most representative subject gaze occurs recurrently thus confirming the hypothesis launched. This is elegantly displayed when viewing the key areas identified by saliency-normalized visual maps for each image set, clearly illustrating the significance of the anchor object during this process. It is naturally anticipated that individual surgeons may use different orientation strategies which is illustrated in the apparent lack of clustering of some of the performance groups in the visual profiling output graphs. However, by using the most representative subject of the high performance group we are able to characterise a quintessential successful behaviour in both NOTES scenarios as in this experiment and in laparoscopic cholecystectomy as in Chapter 4.

In particular, when presented with obscured views of the right upper quadrant the importance of the falciform ligament as a visual orientation cue became apparent and gaze plots indicate how this structure can be related to others in the scene successfully. A similar reorientation strategy was deduced when presented with retroflexed views of the right upper quadrant, with the stomach providing an important anchor reference in relation to the liver and endoscope. When the view is that of retroflexion towards the pelvis, the endoscope and trocar were not only important visual cues to establish the orifice of access but are likely to provide strong cues of rotational orientation in consideration with adjacent structures.

This study may have some important implications on NOTES navigation. It is anticipated that representative successful strategies could be taught to novices thus speeding up the learning process specific to reorientation associated with this technique, as demonstrated for training of orientation strategies in laparoscopic cholecystectomy in the previous chapter. It is anticipated that interventional endoscopists learning NOTES procedures would benefit from learning these strategies as they familiarise themselves with navigating outside the confines of the gastrointestinal tract, to shorten the learning curve associated with NOTES navigation. Moreover NOTES surgeons with the relevant experience who still fall below average performance may be aided by targeted orientation training in the same format as illustrated in the previous chapter.

Finally, the results of this study also provide important data that can be used for designing orientation friendly NOTES platforms arguably more significant than the educational implications, given the general consensus that the flexible endoscope is an inadequate tool for long-term use in NOTES. It is hoped that this data will aid in the design of a NOTES orientation friendly platform combining individual innovative computer-assisted applications such as dynamic view expansion [157] and augmented reality techniques [128,158] to highlight intra-operatively in real time those organs and structures important to the surgeon.

6.5 Acknowledgements

Dr Mark Talamini from University of California in San Diego and his team for the kind use of the human NOTES images used as visual stimuli in this experiment.

Chapter 7 Endoscopic horizon stabilization in Natural Orifice Translumenal Endoscopic Surgery – a randomized controlled trial

This chapter is based on a study submitted for publication in Endoscopy and presented at the Association of Surgeons of Great Britain and Ireland Annual Scientific Meeting in Bournemouth 11-13 May 2011, as referenced in introductory chapter.

7.1 Introduction

Throughout this thesis in the discussion of problems facing the clinical implementation of NOTES, the White Paper published in 2006 [105] by the NOSCAR working group has been repeatedly referenced. This is a credit to the relevance and importance of the recommendations of the working group, as well as recognition of the value in establishing wide research networks with common goals and the ability to promptly disseminate research finding and clinical outcomes. As highlighted in the previous chapters, maintaining spatial orientation was recognised as one of the 12 most important challenges and identified as an essential requirement for any NOTES surgical system. We know that disorientation in NOTES can occur through prolonged navigation with inadequate views, when the operator is working in a retroflexed position (image is upside down), or during off-axis visualisation. What some of these factors have in common is transformation of the image on the roll axis. From conventional surgical teaching we also know that when performing a surgical procedure it is customary to have a stable view with the contour of the liver parallel to the horizon. This is what is taught in laparoscopic training programmes and it has been shown that surgical performance degrades as this view is lost with image transformations on the roll axis [147]. A solution proposed in the White Paper was electronic image stabilization / inversion.

Fowler et al [159] have evaluated a spatial orientation device consisting of an electromagnetic tracker within the endoscope to display the three-dimensional imaging of the shape and orientation of the endoscope. They reported favourable outcomes in a simple porcine transgastric navigational task when using this device compared to control. However, since the publication of the White Paper only two publications have proposed solutions to the problem of image rotation. Tang et al [160] described a live video manipulator software which could perform instant video rotation, vertical or horizontal video inversion, mirror imaging and digital zooming. They reported good image quality of the manipulated images in transvaginal NOTES procedures in this observation and feasibility trial however they did not perform any usability or comparative evaluations. Holler et al [161,162] described endoscopic orientation correction using a tri-axial inertial sensor at the endoscope tip. They performed an evaluation of this Micro Electro-Mechanical System (MEMS) based image rectification system in a comparative porcine study with a task involving trans-abdominal grasping of needle markers in the four abdominal quadrants visualised by a flexible endoscope using a trans-sigmoidal NOTES access. They reported an increased performance with an inferred reduction of complexity of the task when it was performed with automatic horizon stabilization.

The hypothesis to be tested was that performance in a more complex simulated transgastric NOTES procedure would be enhanced with the use of automatic horizon stabilization in a cohort of surgeons and gastroenterologists.

7.2 Methods

7.2.1 Subjects

18 subjects (11 surgeons/7 gastroenterologists) were recruited to participate in this randomized controlled trial taking place in the Perception & Ergonomics laboratory at Imperial College, London. Subjects were either specialist registrars (senior residents) or consultants (attendings). Surgeons had a minimum experience of 50 laparoscopic operations as primary operator and gastroenterologists had performed a minimum of 200 flexible endoscopic procedures. Subjects

were shown a standardized presentation illustrating the experimental task as well as some images of the Endoscopic-Laparoscopic Interdisciplinary Training Entity (ELITE) simulator and an information leaflet before signing appropriate consent to participate.

7.2.2 Experimental Task

The task was performed in the ELITE box trainer simulator [163,164]. The ELITE is a full-size replica model of a human female torso including a gas-tight abdominal wall and transgastric and transrectal access routes to the peritoneal cavity. It contains a complete modular organ package with the ability to perform electro-cautery at the base of the appendix and plane between the liver and the gallbladder. It has been evaluated previously in the context of simulated NOTES surgery and face and construct validation has been established [163,164]. An overview of the abdominal components of the ELITE simulator is illustrated in Figure 7.1a.

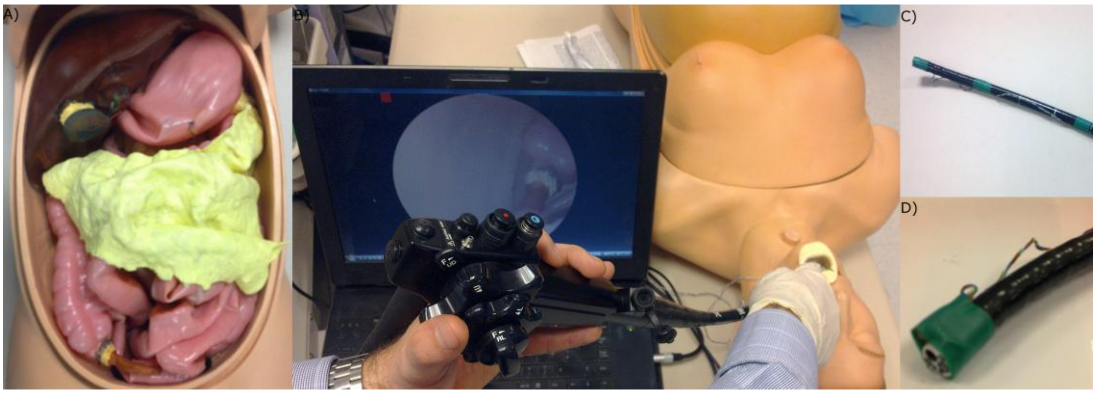


Figure 7.1 a) Overview of the abdominal components of the ELITE simulator with gastrotomy site visibly marked by sutures **b)** Experimental set-up with unaltered endoscopic view **c&d)** Flexible endoscope with IMU mounted at tip

Subjects used a standard single-channel gastroscope (GIF XQ-240, Olympus, Japan). The task consisted of seven sequential steps:

1) Exit from the starting point within the stomach via a gastrotomy previously formed and marked by sutures into the peritoneal cavity
2) Navigation to and identification of the appendix
3) Touch appendix base using a needle-knife (RX Needle Knife XL, Ref 4584, Boston Scientific, IN, USA) to simulate diathermy

4) Navigation to and identification of the gallbladder in retroflexion
5) Application of endoscopic clip to the cystic artery using endoscopic clip applicator (Resolution Clip, Ref 2261, Boston Scientific, MA, USA)
6) Touch plane between gallbladder and liver using needle-knife (RX Needle Knife XL, Ref 4584, Boston Scientific, IN, USA) to simulate diathermy
7) Exit peritoneal cavity into stomach

A scrub nurse was available to aid the operator in changing instruments, opening and closing the clip applicator and deploying/retracting the needle-knife only. The experimental set-up is illustrated in Figure 7.1b. Performance was assessed by time taken to complete each step of the task and number of errors made. An error was recorded when an instrument (needle-knife or clip applicator) was deployed by the operator and came into contact with anything other than the intended target. Each attempt was recorded digitally and evaluation of performance was by two assessors blinded to subject group.

Each subject performed the task once without horizon stabilization software activated and a second time at which point they were randomized to horizon stabilization or control. Randomization was performed using a computer generated randomization sequence and participants were randomized by allocation of a concealed envelope in a 50:50 allocation ratio.

7.2.3 End-points

The primary end-point was the change in overall performance between the first and second attempt (time taken and errors made), and secondary end-points were absolute performances at the second attempt and subjective evaluation of the horizon stabilization software. Secondary analysis assessed differences between specialties and levels of experience.

7.2.4 Horizon stabilization software

Horizon stabilization in the context of flexible endoscopic surgery and the first technical description was by Holler et al [161], in which they use an inertial measurement unit (IMU) externally mounted to the tip of the endoscope, which is the method employed in this study, as illustrated in Figure 7.1c and 7.1d.

The video capture device is used to convert the analogue video signal (s-video) from the endoscope camera stack, into a digital format for use on the computer. It streams these digital images via USB to the software on a host PC. These are subsequently rotated in software, given the measured pose of the endoscope, to maintain a static horizon. The image must have been rotated by a minimum angle from its current orientation otherwise the rotation angle is not changed. This stops small rotations occurring due to noise, and hence introducing movement into the video that isn't present. The image is then cropped using a circular mask. This is done because the output from the endoscopic stack is not purely the image obtained from the endoscopic camera as it contains additional information on the patient as well as time stamps. Cropping removes this extra information that does not need to be rotated. In addition this corrects the centre of rotation, which may not be the centre of the uncropped image. Furthermore, the circular mask hides the fact that the rotation is happening, as straight edges of the image show rotation and these can be distracting to the operator. The amount of image rotation is dictated by the Kalman filter.

The IMU measures the pose of the endoscope with respect to gravity. It measures 5x15x2 mm, and consists of a 3-axis micro electro-mechanical system (MEMS) accelerometer. An ATmega328 8-bit microcontroller (Atmel, CA, USA) is used for communication between the IMU and the PC. The microcontroller serves to arrange the accelerometer data returned by the IMU into packets for transfer to the PC, no processing of sensor data is performed on the microcontroller. The IMU communicates with the microcontroller using a two-wire I^2C digital communication protocol, with the accelerometer sampling rate set at 400Hz. Four wires must be passed along the shaft of the endoscope from the IMU to the microcontroller, two for communication and two for power. The microcontroller communicates with the PC over a virtual serial port, requiring a standard USB cable to connect the two devices. A schematic of this set-up is illustrated in Figure 7.2.

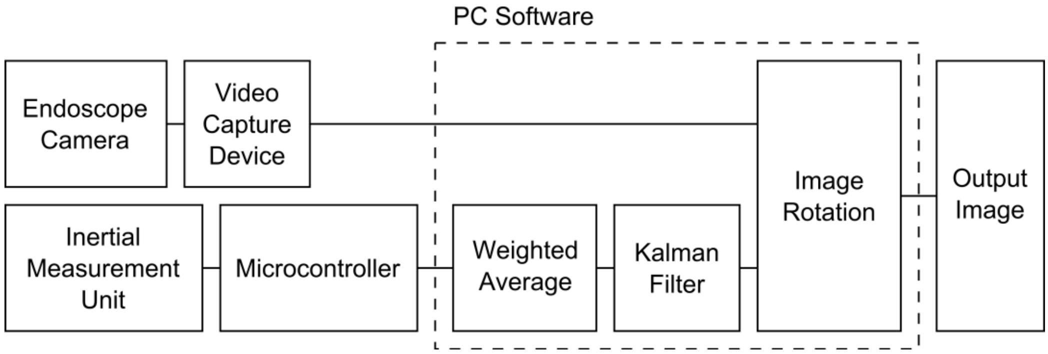


Figure 7.2 Schematic of horizon stabilization set-up

The weighted average is performed because the sampling rate of the sensor is higher than that of the video (400Hz vs 25FPS), therefore the data needs to be down sampled. It therefore takes all sensor information received between the previous frame and the current frame and performs a weighted average, resulting in a single sensor sample for each frame. The weighting is calculated such that the accelerometer values that are closer to 1g are weighed higher than those that are not. Normally at rest the accelerometer should read a magnitude of 1g (acceleration of gravity) but movement causes accelerations to occur and hence this is superimposed with the acceleration due to gravity giving incorrect rotations. This weighted average gives a lower weight to any sensory readings that are affected by additional accelerations. Kalman filter are traditionally used to improve readings from sensors. It contains a model of the system, and from a current value / state of the system it is possible to predict what the subsequent state will be. However, over many steps this can become inaccurate. We use our measurements to augment the predicted state. The expected noise in both the model and measurement determines the weighting towards either estimate i.e. which is more accurate, the measurement or the model and its prediction.

In order to perform horizon stabilization it is first necessary to align the camera vertically to a plum line, or other vertical reference point. This process of calibration is performed manually every time the system is used and establishes the relationship between the camera and IMU coordinate systems. As the force of gravity constantly acts on the accelerometer, when static, the measured acceleration will have a magnitude of 1g. The angle between the current measured vector associated with gravity and the calibration vector is that by which the endoscope image is rotated to stabilize the horizon. However changes in velocity of the endoscope will produce additional acceleration which is superimposed with the constant acceleration due to gravity. As the gravity component is inseparable from this additional component errors can occur in the angle calculation. However, down-sampling of the sensor data is necessary as the sampling rate is much faster than the camera frame rate (400Hz vs 25Hz). This data redundancy allows the data to be filtered in order to avoid errors associated with movement. A weighted average is used [161] as it biases the average of sensor values within one image frame towards a magnitude of 1g. As mentioned, the weighting for each set of sensor data is inversely proportional to the deviation of their magnitude from 1g. Hence those sensor data values affected by motion are effectively ignored. To avoid unwanted motion in the image from small angle changes due to sensor noise when the endoscope is stationary a minimum angle change threshold and Kalman filtering are introduced. This results in a smooth output image free of jerky movements during all types of endoscope manipulation.

7.2.5 Statistics

Comparisons between individual variables were performed using the Mann Whitney U test and correlations of continuous variables were determined by nonparametric linear regression. Statistical analyses were performed using SPSS v18.0 (Chicago, USA). Differences were considered statistically significant at $p<0.05$.

7.3 Results

7.3.1 Primary end-point

When horizon stabilization was turned off there was a median improvement of 42.4% in time taken and 38% in number of errors made from the first to second attempt, however with the software turned on there was a statistically significant deterioration of 4.9% ($p=0.038$) in time taken and an increase in errors made of 183% ($p=0.689$). The second attempt was performed faster with the software turned off (median 350 v 796 sec; $p=.085$) with overall fewer errors made (median 1 v 3; $p=.079$).

7.3.2 Secondary end-points

Gastroenterologists performed the task faster than surgeons at the first attempt (median 748 v 568 sec; p=0.026) with no difference in errors made (median 2 v 3; p=0.645), however there was no difference in time taken or errors made at the second attempt and there was no difference in overall improvement (learning) between the attempts (41 v 21.4%; p=.821)

As illustrated in Table 7.1, for gastroenterologists, although both performance parameters were superior without horizon stabilization these did not reach statistical significance. Similarly for surgeons, performance was more favourable without the horizon stabilization software. The median change between the attempts for surgeons with the horizon stabilization software was an improvement of 15.4% although the mean change was actually a deterioration of 78.5%.

Table 7.1 Performance at second attempt following randomisation per group. Percentage change indicates change in time between first and second attempt

	With Horizon Stabilization			**Without Horizon Stabilization**		
	Time (median)	Errors (median)	% change	Time (median)	Errors (median)	% change
Overall	796	3	4.9	350	1	-42.4
Surgeons	805	3	-15.4	431	1.5	-35.3
Gastroenterologists	579.5	5.5	22.5	335	1	-42.4

There was no statistically significant correlation between time taken and experience as first laparoscopic operator (rho=.096; p=.708), laparoscopic assistant (rho=.168; p=.505) or total number of flexible endoscopy experience (rho=-.310; p=.211). There was also no statistically significant correlation between number of errors made and experience as first laparoscopic operator (rho=-.090; p=.724), laparoscopic assistant (rho=-.122; p=.631) or total number of flexible endoscopy experience (rho=.142; p=.575).

Subjectively all subjects randomized to horizon stabilization complained of two problems. The first and most troublesome was that the endoscopic controls did not correspond to the conventional movements while viewing the rectified image i.e. up did not correspond to up, and furthermore they did not remain constant throughout the task as they were dependent on the orientation of the endoscope. Secondly the exit point of the instruments (usually at 7 o'clock on the monitor) was altered and variable depending on endoscope position.

As can be seen from Table 7.2 the greatest difference in time between subjects during the second attempt was at stage 5 (p=0.058) which was clipping of the simulated cystic artery. This is the most complex step operatively and requires fine navigation of the endoscope whilst in retroflexion to achieve optimum position for the placement of the clip.

Table 7.2 Median time taken (seconds) per stage of the procedure for all subjects

Stage	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Without software	13	28	43	31	95	99	14
With software	15	38	60	39	172	91	15

7.4 Discussion

The results of this randomized controlled trial indicate that overall performance in this simulated transgastric NOTES task actually deteriorates with the use of horizon stabilization software. Subjects reported significant problems using horizon stabilization mainly concerning navigation control and instrument exit point. It appears that the effects of these changes outweighed any benefit in performance from the presumed increased likelihood of maintaining spatial orientation due to horizon stabilization.

One way of overcoming the subjective problems reported by the participants may be to display twin monitors, with the rectified and unaltered images next to each other, so during navigation the operator can rely on the unaltered image to guide control of the endoscope. This would however mean that navigation would sometimes occur without a straight horizon, perhaps degrading performance compared to a corrected view. A more elegant solution however would be to decouple the visuo-motor control axis, by using a robotic endoscope interface. This would allow for correction of the motor control as the image is manipulated to stabilize the horizon, thereby realising the full benefits in orientation of a stable horizon whilst maintaining a customary control mechanism. This highlights the importance of developing improved mechatronically controlled devices with seamless instrumental control if NOTES is to make a realistic impact in the future of MIS.

It is widely accepted that gastroenterologists rely less frequently on a standard horizon view since due to the tubular structure of the gastrointestinal tract, standardizing the roll axis rarely makes a difference. Surgeons however prefer a standard laparoscopic view when performing MIS [147]. For operative/interventional NOTES procedures therefore, the ability to aid the operator in obtaining an optimal view will be a requirement for any NOTES-specific platform.

Due to the relatively small sample size, and to avoid bias due to individual variability as much as possible, it was decided to allow all subjects to perform the task once and then randomise them to horizon stabilization or control for the second attempt. Although it is accepted that there is an individual variability in learning it was presumed that this was less significant than individual variability in task performance and therefore it was decided to use the change of performance between the first as second attempt as primary end-point.

This evaluation of horizon stabilization did not yield the same results as the initial validation by Holler et al [165], which concluded it to be beneficial. In their validation subjects were presented with a view of both the rectified and non-manipulated images during navigation in four quadrant peritoneoscopy and the needle targets were grasped using conventional trans-abdominal laparoscopic instrumentation, not instruments from the flexible endoscope. The flexible endoscope was used for visualisation alone and did not contribute to any further operative manoeuvres. Therefore, the derived benefit here is likely to be due to the correction of the image at the point of the task, as we know that laparoscopic performance is optimum with correct orientation of the viewing endoscope [147].

The fact that there was no difference in second attempt performance based on level of training or specialty is in concordance with the results presented in Chapters 3, 4 & 6, and likely reflects a combination of the relative novelty of the NOTES approach to both surgeons and gastroenterologists as well as the fact that most participants in this study were experienced enough to have reached their innate proficiency in orientation. The fact that the difference in performance between both groups was most marked for stage 5 (clipping of cystic artery), which represented the most complicated step operatively, highlights the need for fine motor control of the endoscope during surgical NOTES procedures.

An issue with using an IMU for horizon stabilization in its current form is that it has to be secured to the outside of the endoscope, which inevitably leads to an increase in diameter of the overall device. Although no problems were encountered in this simulator study, the increase in size may lead to increased tissue trauma at the gastrotomy site or difficulties in passing it through an access overtube or port. It is also imperative that the IMU is secured to the endoscope in a fashion that avoids exposing surrounding tissue to the relatively sharp edges of the IMU during navigation. In future robotic devices a solution to this may be internalisation of the sensor within the operative platform as part of a combination of hardware incorporated to decrease disorientation during MIS.

The potential benefit of horizon stabilization during NOTES procedures is clear however its use is not supported in the context of direct application to current design of flexible endoscopes by the results of this experiment. Further work should focus on establishing the mode of application of the software, for instance, would it be beneficial to apply horizon stabilization intermittently as controlled by the operator? Furthermore, the potential uncoupling of the visuo-motor axis to allow for conventional endoscopic control should be explored and preferably in the context of a more complex surgical procedure where the true benefit of maintaining correct orientation and visual alignment can be demonstrated.

7.5 Acknowledgements

Special thanks to Alexander Warren for the construction and assembly of the horizon stabilization hardware and software. Also thanks to Professor Feussner, Professor Friess, Dr Sonja Gillen and Dr Adam Volka from the Department of Surgery, Klinikum rechts der Isar, Technische Universität München, Munich, Germany for their contribution to this experiment.

Chapter 8 Conclusions and future work

8.1 Achievements of this thesis

Without a doubt, the most important recent advance in abdominal surgery has been the introduction and evolution of MIS. In the last 20 years laparoscopic procedures have gone from an experimental concept to gold standard for many operations with an exponential rate of technological innovation. It is likely that as MIS evolves, future abdominal surgery is going to be increasingly reliant on computer-assistance to enhance perception of the operative environment. This will not only aim to restore sensory input to those levels seen in open surgery, but potentially to augment perception to an even greater level than this, thereby decreasing the likelihood of operator error and patient morbidity and mortality. However before it is possible to enhance perception in a minimally invasive surgical environment, it is necessary to define the contributing factors and furthermore to understand specific causes and effects on these.

In this thesis, the paradigm of human disorientation as applied to MIS has been investigated, with particular reference to laparoscopic cholecystectomy and common early clinical NOTES procedures. A review of the literature was performed which included important studies from the psychology, aviation and the virtual worlds literature. The relevance of the problem of disorientation in MIS was highlighted in a review of the medical literature and current understanding of the concept was defined.

In Chapter 3 of the thesis, the orientational paradigm was evaluated in a model not requiring human anatomical knowledge but with similar geometric and image properties to NOTES surgery in non-medical and medical subjects. A Hidden Markov model-based algorithm was described, evaluated and validated to profile visual behaviour captured using eye-tracking data. This algorithm was shown to accurately profile and compare orientation behaviour by comparing gaze fixation sequences. This is the first published quantification and description of orientation using this data stream and represents an initial step in the quest to objectively assess and understand this behaviour.

In Chapter 4, orientation was investigated in the context of a laparoscopic cholecystectomy using gastrointestinal surgeons as subjects. Eye-tracking data was used to capture psychophysical behaviour and the previously validated profiling algorithm was used to discern orientation strategies at specific and crucial stages of the operation. Significant visual cues and orientation strategies at each step were evaluated and quantified. This is the first objective evaluation of orientation in surgery and has enabled high performance behaviour to be described. The implications of these data are the use of this evaluation methodology as an assessment tool to identify those individuals who may benefit from structured training. Furthermore these high performance orientation strategies may be used in an educational setting to improve novice surgeons as well as those identified as performing below average.

Consequently, in Chapter 5, specific orientation strategies associated with high performance at specific stages of a laparoscopic cholecystectomy were taught in a randomized controlled trial of final year medical students. The results of this study indicate that orientation strategies can not only be effectively taught to novice surgeons using a targeted multimedia-based tutorial, but their performance at this task can increase to the level of a surgeon with several years experience in laparoscopic surgery. This is the first study which investigates education of perception in relation to MIS. It is assumed that novices with a decreased cognitive burden will have an increased capacity to develop technical skills compared to those who are more likely to be disorientated. For that reason consideration should be given to including orientation training in a standardized minimally invasive surgical curriculum.

The potentially more disorientating scenario of NOTES operations were studied in Chapter 6. Here, orientation strategies were profiled, compared and quantified in human NOTES cases using the previously validated algorithm in expert gastrointestinal surgeons. Due to the additional complexity of the operative scenarios, scene saliency was considered to expose the image features that significantly influence orientational ability and the particular strategies associated with high performance. This is the first quantifiable evaluation of spatial orientation and operator behaviour in NOTES, whereby high performance behaviour was described for common transvaginal and transgastric operative approaches. Implications of these outcomes on education as shown in Chapter 5 are clear and furthermore these data may prove crucial in the development of innovative technology to combat disorientation in future NOTES operating platforms.

The final experimental chapter evaluates one such innovative technology. Here, it was shown that the application of endoscopic horizon stabilization software in a navigational and resectional task in a simulated NOTES model was not associated with an increase in performance in a heterogeneous group of surgeons and endoscopists. These results are likely a reflection of the method of application of the software rather than the benefit of the concept and important suggestions for future applications in NOTES are described based on the conclusions of this study.

The limitations of the research have been discussed in each experimental chapter. Of particular importance in the evaluation of this work is to acknowledge the assumptions associated with using eye tracking as a research tool in the investigation of attention and behaviour, and specifically the impact of experimental design on both quality and applicability of the data generated. Further potential limitations discussed are the use of static rather than dynamic images, although this arguably is preferential within the context of disorientation and surgical error, and the reasons for this have been elaborated on in Chapters 3 and 6 in particular. A final consideration is that orientation strategies are likely to vary at an individual level and therefore a successful strategy in one surgeon may result in disorientation in another and vice versa. It is also accepted that some individuals will use highly atypical successful strategies in orientation, and the above considerations may be greatly influenced by gender, personality, experience and physiology. With this in mind the investigations into orientation strategies have focused on cohort level profiling and subsequently group teaching to allow for individual variations, and to expose the most representative and generalizable individual strategies which are likely to be most beneficial for the largest proportion of surgeons.

8.2 Future perspectives

Although the problems associated with disorientation in MIS have been recognised by many no efforts have been made to understand the behavioural patterns which result in errors and consequently patient morbidity and mortality. This thesis represents the first steps in both the understanding as well as attempts to correct the deterioration of performance associated with disorientation in MIS. As such it is stimulating and logical that this research stream has unveiled a number of important themes for further study:

8.2.1Quantificaton of orientation strategies in MIS procedures

As seen with the introduction of NOTES, disorientation is likely to be an increasingly important contributing factor to cognitive load as MIS advances and becomes more technologically-driven. It is therefore of paramount importance to identify specific operations which have critical steps associated with high morbidity due to operator disorientation. As demonstrated for laparoscopic cholecystectomy in this thesis, high performance orientation strategies need to be quantified for these critical steps of other MIS procedures.

8.2.2 Demonstration of an increased technical skills-transfer following orientation training

In this thesis it has been demonstrated that targeted orientation training increases performance of novices at this particular task. It is presumed that this will lead to a decrease in cognitive load and therefore a presumed higher capacity to learn other skills such as operative techniques. Further work should focus on illustrating a difference in the learning curve of advanced technical skill acquisition in surgeons with enhanced orientational skills through structured training.

8.2.3 Real-time analysis of eye tracking signal

In this thesis eye tracking data are analysed from a temporal perspective and in the context of placement of fixations and hence presumed allocation of attention over time. As illustrated in this thesis this is a very useful way of deducing higher thought processes such as orientation strategies. However, there is scope to expand on the analysis of this data to obtain an even more meaningful insight to human behaviour. Future work should focus on investigating the quality of the signal as well as temporal changes. Characteristics such as blink rate, pupil diameter, fixation rate, saccade rate, and vergence are only some of the parameters that can be considered to compute the quality of the signal itself. It has already been shown that through comparing very basic eye parameters the difference between novice and expert behaviour can be inferred in surgery [36]. Further research should focus on refining the eye parameters recorded and analysis pathways used to optimise the significance and usefulness of the signal to characterise behavioural patterns. It is entirely possible that by combining the quality of a carefully refined signal with its temporal changes we are able to deduce a psychophysical “finger-print” for disorientation. Furthermore, through the right experimental conditions we should be able to deduce the “finger-print” for other physical states associated with cognitive impairment or error, such as fatigue, and once we can detect these states we can combine eye tracking technology in the operating room workflow to warn of dangerous behavioural patterns before error occurs.

8.2.4 Integration of multiple innovative solutions in a disorientation tool for MIS operating platforms

Endoscopic horizon stabilization as trialled in this thesis represents an innovative solution to the transformation of the image on the roll axis, which is one component or causative factor of disorientation in MIS. There are however solutions to other factors which increase disorientation, and these should be combined for maximum translational effect. Further work should focus of merging a number of individual solutions in a “disorientation tool” which can be applied to any MIS operating platform. This will likely include hardware such as sensors as well as associated software such as dynamic view expansion and augmented reality.

8.2.5 Clinical NOTES applications

In tandem with the research work outlined in this thesis, myself and Mr James Clark have been responsible for the clinical NOTES investigation at Imperial College in a team led by Professor Darzi and Dr Julian Teare. Since this research group was established in early 2008, NOTES has moved from the ideological and experimental into the clinical arena with multiple feasibility trials taking place around the world. Early results appear encouraging, and the transvaginal access route appears currently most favoured due to its established safety parameters in gynaecological surgery. Following 3 years of extensive simulator, ex-vivo, in-vivo and clinical research, ethical approval was granted to evaluate feasibility and clinical outcomes of transvaginal NOTES surgery at Imperial College.

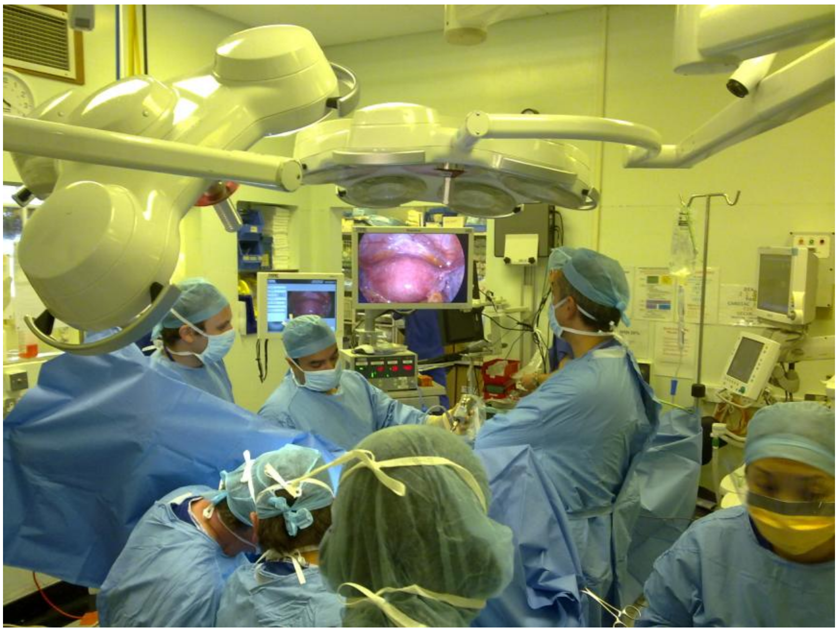


Figure 8.1 Operative room set-up for the first United Kingdom transvaginal hybrid cholecystectomy, June 2010

On the 4th of June 2010 a 21 year old female patients with uncomplicated biliary colic underwent a transvaginal hybrid cholecystectomy, which was the first hybrid NOTES procedure performed in the United Kingdom. The operation was performed by a multidisciplinary team in MIS, gynaecology and interventional endoscopy. The operation lasted 127 minutes and there were no peri-operative complications or morbidity. The patient received paracetamol analgesia only and was discharged on post-operative day 1. At 1 month follow-up there were no abdominal or gynaecological symptoms and no visible abdominal scars.

Figure 8.2 Delivery of the gallbladder transvaginally in the first United Kingdom hybrid NOTES cholecystectomy

The trial is ongoing with some very encouraging results particularly relating to post-operative pain, however, the shortcomings of current flexible access technology has been increasingly apparent. Currently we are able to perform these hybrid operations safely although any increased complexity or decrease in trans-abdominal assistance would prove technically very difficult and potentially unsafe using current instrumentation. Our current expansion of clinical applications besides transvaginal cholecystectomy and appendicectomy will involve using the transvaginal access route for specimen extraction and anastomosis for benign right sided colonic resections, thereby further minimising the trauma induced by the abdominal wall incision used for this purpose, and in our animal laboratory we are further exploring the concept of a hyper-redundant image-sensing flexible access robotic device to limit the inadequacies of current technology.

For NOTES therefore to realise its full potential, surgeons have to wait for technology to catch up with ideological innovation before embarking on more complex procedures than the hybrid transvaginal feasibility studies currently taking place. In particular, instrument design should be at the focus of our attention and strong collaborations with industry are necessary to expedite and facilitate this process. Not only do we require flexible access operating platforms with multimodal image integration, but a whole new tool-kit of flexible access instrumentation. This should focus on basic surgical principles such as retraction and exposure with integration of triangulating interchangeable instrumentation such as forceps, graspers, needle-holders, staplers and suturing devices as well as focused energy delivery systems. The ergonomics, usability and design of this instrumentation are crucial to overcome the additional burdens of NOTES and flexible access surgery, and are areas which must be rigorously explored in MIS laboratories with interests in novel technologies. In this regard, our effort should be directed to cultivating and motivating technological innovation rather than venturing out heroic effort with inadequate instruments that may put patients at risk. As frustrating as this may be, it is of vital importance not to proceed with surgical interventions which are not supported by the technology currently at our disposal, as jeopardizing patient safety at the early stages of clinical applications may put at risk the realisation of the full benefits of NOTES.

8.3 Conclusion

MIS is evolving at a rapid rate, and more minimally invasive procedures are often associated with increased procedural complexity and cognitive burden on the operator. As a result surgeons are more prone to disorientation, an issue which is increasingly recognised by the MIS community.

In this thesis perception and orientation in MIS have been explored by first contextualising these relatively under-investigated surgical phenomena through reviewing current evidence from other industries such as aviation and psychology. An estimate of the impact of disorientation in laparoscopic cholecystectomy is outlined and discussed in the context of evidence available in the surgical literature.

Subsequently a method for quantifying and profiling orientation as a behavioural pattern was validated in a simulator model and used in the setting of specific stages of a laparoscopic cholecystectomy to describe high performance outcomes. It was shown that these orientation strategies could be taught to novices in MIS in a concise and focused multimedia tutorial and thereby increasing their performance to the level of an expert surgeon with several years of experience in MIS.

Orientation was then investigated in NOTES, and the concept of image saliency was introduced to evaluate effective orientational behaviour during common transvaginal and transgastric scenarios. Performance outcome could again be correlated to specific psychophysical behavioural patterns which have relevance to education, as shown in the example of laparoscopic cholecystectomy, as well as in the construction of NOTES-specific operating platforms. Subsequently, a tool to decrease disorientation in NOTES, endoscopic automatic horizon stabilization, was evaluated in a simulator model of NOTES navigation and operative manoeuvres. Finally, further research areas in eye tracking applications for MIS, education in orientation, clinical NOTES and disorientation tool innovation were summarised to conclude the thesis.

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