

Imperial College London
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**Designing and Evaluating HEaring and
LIstening eXperience (HELIX): A co-designed
auditory-cognitive training application**

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A thesis presented for the degree of Doctor of Philosophy

Statement of Originality

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Abstract

The true nature of the relationship between age-related hearing loss and cognitive impairment outside of the expected ageing process is still undetermined. Whilst it is understood that the two functional abilities of peripheral hearing loss and cognitive performance are linked, the focus has been on supportive technologies such as hearing aids and how this may dampen or prevent additional cognitive decline; with recent research findings discouraging a link between cognition and hearing aid use. This focus on exploring supportive, rather than empowering technologies, ignores a potential window of opportunity in mid-life whereby hearing and cognitive health can be targeted via auditory-cognitive training.

Traditional computerised auditory-cognitive training programs have been laboratory-based and criticised for lacking stimulation and interest. There is scope to utilise another approach to auditory-cognitive training via serious games. Using this approach has potential to ensure programs are stimulating, fun to play and maintain interest over an extended period of time. Ensuring compliance with an auditory-training programme that is relevant to the user has scope to generate high compliance.

This PhD work aims to explore how a serious game could house an auditory-cognitive training program targeting speech-in-noise recognition, working memory and attention. In the first stage, a participatory design process was used to elicit the facilitators and barriers of a new training programme and the specific user design elements required to make it a success. After piloting a beta-version, a second stage utilised a randomised-controlled trial with an additional qualitative component to evaluate whether using the application over a 4-week period resulted in improved speech-in-noise perception, cognitive performance, communication confidence and quality of life.

This thesis is focussed on the design and evaluation of the HEaring and Llistening eXperience (HELIX) application. The lessons learned across both stages provide insight into the future development of auditory-cognitive training programmes.

Acknowledgements

I would like to thank my supervisor Lorenzo Picinali for all of his support, guidance and wisdom over the past 7 years. He gave me the opportunity to study for this PhD on a part-time basis to allow me to continue my clinical career. I am now finishing this PhD as the Head of Audiology Services and Consultant Healthcare Scientist, which would not have happened without this opportunity.

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Acronyms

ACE-III Addenbrooke’s Cognitive Assessment. 9, 54, 66

AD Alzheimer’s Disease. 7, 8, 10, 14–17, 25, 26

ANOVA Analysis of Variance. 77, 78

CCP Communication Confidence Profile. 74, 79

CG Control Group. 66, 78, 89, 95

dB Decibel. 3, 31, 54, 55, 69, 73

DTT Digit-Triplet-Test. 3, 5, 54, 55, 59, 73, 74, 88, 91, 92, 94–99

ELU Ease of Language Understanding. 62

HELIX HEaring and LIstening eXperience. 3, 49, 56, 58, 59, 63, 64, 66, 68, 74, 78, 79, 81, 83–90, 93

JSON JavaScript Object Notation. 71

kHz Kilohertz. 54

LACE Listening And Communication Enhancement. 19, 20

MCI Mild Cognitive Impairment. 14–18, 26, 40

MMSE Mini-Mental State Examination. 9, 14

MoCA Montreal Cognitive Assessment. 9, 14

NIHR National Institute of Health Research. 55, 65, 74

PTA Pure-Tone Audiometry. 3, 10, 52, 65

QuickSIN Quick Speech-in-Noise. 3, 21, 51, 92, 97, 98

RCT Randomised Controlled Trial. 3, 5, 20, 24, 25, 58–60, 62, 94–97

RMS Root Mean Square. 55, 72

SiN Speech-in-Noise. 3, 54, 61–64, 88, 92, 98, 99

SNR Signal-to-Noise Ratio. 3, 19, 31, 54, 55, 69, 73, 88, 95

TG Training Group. 66, 68, 78, 88, 95

UEQ User Experience Questionnaire. 76, 80, 88, 89, 96

WHO World Health Organisation. 6, 24

WHOQOL-AGE World Health Organisation Quality of Life - Age. 74

Chapter 1

Introduction

1.1 Motivation and Objectives

As Audiologists working with the NHS we routinely see patients across their lifespan, which not only includes expected healthy ageing, but also the spectrum that accelerated cognitive decline and diagnosed dementia have on patients' quality of life. This is not just related to their hearing health but their overall general health. This allows Audiologists as a profession, a unique insight by witnessing how patients age and the effects that other health conditions can have on their hearing, in addition to how their hearing rehabilitation can impact on other comorbidities. The following motivations and objectives of this thesis are based on the literature review which is reported in Chapter 2.

It has been widely acknowledged in the audiology community that hearing loss, hearing aid usage and cognitive performance share a link, although we are yet to determine what this link is and even then so, whether it can be manipulated to improve either auditory or cognitive performance or even both, yet perhaps neither can be changed once decline has begun. Nevertheless, this area deserves more research into not just the effects of hearing aids on cognitive performance, but cognitive hearing science more generally and the mechanisms that could be harnessed for change. Research around prevention should be prioritised, taking a proactive rather than reactive approach.

One area that meets the needs of a proactive approach is practising regular auditory-cognitive training. Any health behaviour changes like smoking cessation, weight loss and diet control must be attractive, attainable and maintainable by the intended user groups, otherwise it is set up to fail, regardless of the published benefit. Therefore in order to create a new auditory-cognitive training programme to test, steps should be taken to ensure the content, accessibility and expectations of the programme are relevant to the intended user groups. Only utilising literature that has gone before to design new programmes will not meet the needs of the target group and is likely to fail. There is scope to employ a participatory design approach to harness not only the literature, but the input of key stakeholders that will be involved in using, promoting or researching auditory-cognitive training.

The overall objectives of this thesis were:

1. To adopt a participatory design approach to understand the facilitators, barriers and design content required for a new auditory-cognitive training application for those at risk of age-related hearing and/or cognitive decline.
2. To evaluate the impact a co-developed auditory-cognitive training application would have on the auditory and cognitive performance of those at risk of age-related hearing and/or cognitive decline
3. To gather qualitative data on how using a co-developed auditory-cognitive training application impacted sensory health behaviour change
4. To complete the co-design and evaluation process and reflect on lessons learned for future development of the auditory-cognitive training programme and for the wider auditory-cognitive training application developer community.

1.2 Contributions

This thesis has had both expected and unexpected contributions, the latter being mainly due to the Covid-19 pandemic.

In order to achieve the overarching objectives of this thesis, a beta-version of an auditory-cognitive training programme was co-designed with relevant stakeholders and developed through TestFlight via the Apple Store. HEaring and Llistening eXperience (HELIX), went through a short pilot and was then fully evaluated via a Randomised Controlled Trial (RCT). The results of the evaluation discussed in Chapter 5 have ramifications not only for the future development of HELIX, but also useful lessons learned for other developers in the field of auditory-cognitive training.

Somewhat unexpectedly, due to the Covid-19 pandemic, the second major contribution of this thesis was the development of a new, online version of the Digit-Triplet-Test (DTT). The original plan was to complete the RCT using standardised tests, such as Pure-Tone Audiometry (PTA) to screen and assess hearing ability and Quick Speech-in-Noise (QuickSIN) to assess Speech-in-Noise (SiN) performance. Due to the timing of the pandemic and restrictions imposed on face-to-face testing capacity within NHS hospitals for research, it was necessary to explore alternative methods of testing. The DTT has been used to assess SiN in a number of previous studies, but has yet to be made freely available.

Chapter 4 of this thesis explains the process in developing a version of the DTT that could be accessed by participants with results stored on a secure server for research purposes. This involved initially recording stimuli by the researcher, however it was prudent to engage with the audio research community to access recordings that had already been validated and used by other researchers [54]. Following collaboration with a developer within the Audio Experience Design team at the Dyson School of Design Engineering, two online versions of the DTT were launched. The first was specific to this thesis and allowed results to be retrieved for analysis. The second version was a free to access site, in which results were not recorded and stored, but allowed participants to download a PDF of all of their responses and overall score in a dB Signal-to-Noise Ratio (SNR) score. Whilst this particular version hasn't been validated as a diagnostic test, it is recognised as a way of measuring performance over time. This is an improvement over the number of free to use DTT online tests often utilised by private audiology providers, whom instead of providing a numerical result, use a statement as a result such as suggesting the user book in for a full hearing test.

The final contribution worthy of note for this thesis, is the unexpected, but welcome resonance it has had across London which has resulted in a patient pathway change for patients accessing cognitive assessments at the Barking, Havering and Redbridge University Hospitals NHS Trust (BHRUT). Having spoken about the potential relationship between age-related hearing loss and accelerated cognitive decline at professional forums, professional advice was given to the dementia assessment team at BHRUT, who have since successfully implemented routine hearing screening in memory clinics. This has been a successful multi-professional approach between nursing and psychiatrist colleagues, to ensure timely audiological diagnostics and interventions for patients referred for memory assessments. There are plans to expand this initiative across London in collaboration with NHS England.

1.2.1 Peer Reviewed Contributions Related to this Thesis

- Journal Article - Frost, E., Porat, T., Malhotra, P and Picinali, L. A novel auditory-cognitive training app for delaying or preventing the onset of dementia: Participatory design with stakeholders. *JMIR Human Factors*, 7(3), 6 2020. DOI: 10.2196/19880
- Journal Article - Frost, E., Porat, T., Malhotra, P., Poole, K., Menon, A and Picinali, L. HEaring and LListening eXperience (HELIX): Evaluation of a co-designed serious game for auditory-cognitive training. *Quarterly Journal of Experimental Psychology (QJEP)* - under revision.
- Conference Presentation - HEaring and LListening eXperience (HELIX): Co-production and evaluation of a gaming app. 12th-15th June 2022. 6th International Conference on Cognitive Hearing Science for Communication (CHSCOM)

1.3 Thesis Structure

This thesis is divided into the following chapters:

Chapter 2 provides a critical review of the literature which provides the reasoning and justification of the other chapters.

Chapter 3 describes Stage 1 of the project, which was the participatory design phase. This explains how the application was co-developed with relevant stakeholders. This chapter also includes pilot work that was carried out. This design phase was published in a peer-reviewed journal article [27].

Chapter 4 is dedicated to explaining how the Covid-19 pandemic disrupted the intended work and the mitigations and adaptations that were put into place to allow continuance of the work. This includes developing a new online version of the DTT.

Chapter 5 describes Stage 2 of the project, which was a RCT plus paired semi-structured interviews. This trial was to evaluate the effectiveness of the application on a number of outcome measures. A manuscript was submitted as part of a Special Interest Issue to the Quarterly Journal of Experimental Psychology and is currently under revision at time of writing.

Chapter 6 concludes the work from both stages, drawing together the overall findings, lessons learned and directions for future work.

Chapter 2

Literature Review

2.1 The Global Problem

Globally approximately 50 million people live with dementia. This figure is projected to rise to 82 million people by 2030 (World Health Organisation, [WHO] [93]. Currently there is no treatment available to cure or prevent dementia. The WHO has classified dementia as a public health priority with actions to reduce the risk of developing dementia, increasing awareness, diagnosis, research and innovation.

Early diagnosis, intervention and eventually prevention could not only improve the quality of life for the individuals affected, but also the families involved. Family caregivers are at high risk of developing depression themselves. Given the rising numbers of projected dementia diagnoses, high quality interventions could reduce the demand on health and social care services in the years to come, for all those affected by dementia.

A commission by The Lancet [48] was tasked to investigate and consolidate the global emerging evidence on the prevention, intervention and care of people living with symptoms of dementia. They concluded that 35% of dementia diagnoses are potentially preventable, using 9 risk factors with the capability of modifying the diagnosis of dementia. Of those 9 risk factors mid-life hearing loss was the highest potentially modifiable factor at 9%. Mid-life hearing loss is defined

as a mild to moderate peripheral sensorineural hearing loss in people aged 55 and over. This is attributed to age and is often referred to as presbycusis. In an update paper by Livingston et al [47] three years after the initial findings, the number of modifiable dementia diagnoses rose to 40%, with mid-life hearing loss remaining the highest potentially modifiable factor at 8%. In comparison, other modifiable factors in later life included smoking (5%), depression (4%) and social isolation (4%).

The emerging evidence from Livingstone et al.[47][48] concurs with previous research that had suggested a hearing loss can increase in the risk of developing dementia in later life by up to 5 times. Although hearing loss emerged as the highest modifiable risk factor for developing dementia, the causality in this relationship is still unknown. As is whether any form of rehabilitation, either through hearing aids, auditory training or assistive listening devices could delay or prevent the onset of dementia symptoms [48].

2.1.1 Theoretical Position

Despite the gathering research on hearing loss and cognitive decline, there is still no evidence from the literature to prove causality. There is, however a general expert consensus on four hypotheses as to how hearing loss and developing cognitive decline may be related. These are the 1. common cause hypothesis 2. cognitive loading hypothesis 3. cascade or social isolation hypothesis 4. overdiagnosis or harbinger hypothesis [85].

Common Cause Hypothesis

The first is a coincidental relationship associated with neurodegeneration in the ageing process. There is a proposed likelihood that as one ages, the neural processes for hearing and cognition decline independently of each other and are not in fact related. If this is true, then it would also suggest that a treatment for either hearing aids or cognitive decline would be exclusive of each other. Brenowitz, Filshtain & Yaffe et al. [8] conducted an analysis on the genetic traits of Alzheimer's Disease [AD] and hearing loss using a UK Biobank sample of 80,074 participants.

Whilst their main finding was that there was no evidence to demonstrate a genetic risk for hearing loss that affected cognitive performance, they did conclude that a genetic risk for AD did affect speech in noise performance. These findings lend support to the common cause of their being shared aetiologies between the ability to process speech in noise and cognition in a pre-dementia population.

Cognitive Loading Hypothesis

The second hypothesis is that of Cognitive Loading, which originated in educational psychology by John Sweller in 1998 [79]. The theory suggests that the working memory can hold only a limited amount of information at one time, and that any additional information will cause the working memory to become overloaded and ineffective in absorbing extra instruction. This mechanism can be attributed to hearing and cognitive impairment as it is known that an age-related hearing loss predominantly affects the speech frequencies. Listening to conversation especially in background noise demands greater cognitive resource on the working memory. It is therefore proposed that this increasing demand on the working memory causes a shift in the cognitive resources the brain has towards processing the degraded speech signal, in turn leaving less resources to devote to cognitive tasks resulting in cognitive impairment.

The evidence to support this theory is, however limited. A systematic review of the available evidence [59] on whether a hearing loss affected listening effort and secondly, whether a hearing aid affected listening effort further, found the 41 published studies were of poor quality.

One possible investigative measure of cognitive load during listening tasks is pupillometry. Eye tracking can be used to measure the dilation of the pupils during listening tasks on the premise that as cognitive demand becomes greater, pupils will dilate. Van Engen & McLaughlin [88] used pupillometry across a sample of young and older adults with hearing loss. As the listening task became more difficult with a higher degradation of the speech material there was a higher cognitive load recorded from the pupil dilations.

Cascade Hypothesis

The third theory is that of the Cascade hypothesis, sometimes referred to as the social isolation hypothesis, due to the withdrawal of the person from social situations. Similarly to the cognitive loading hypothesis, this third hypothesis centers on the difficulties a person with a hearing loss experiences in social situations. Difficulties in hearing conversations, especially in noise, can make it increasingly difficult for that person to participate in social activities. As hearing speech in background noise, even with digital hearing aids is challenging, a person can withdraw from outdoor activities or interactions leading to social isolation, which consequently increases atrophy in the brain. As one factor creates another a cascade effect is created.

Over-diagnosis or Harbinger Hypothesis

The fourth and final hypothesis is the over-diagnosis or harbinger hypothesis. Cognitive impairment is generally diagnosed through a series of neuropsychological tests, such as the Addenbrooke's Cognitive Examination [ACE-III][35], the Mini-Mental State Examination [MMSE] [26] or the Montreal Cognitive Assessment [MoCA][56]. Administering these tests relies on the participant having sufficient auditory processing to understand and respond appropriately to the questions asked of them. On the MMSE, for example, participants are asked to repeat the phrase *no ifs, ands or buts*. It is commonly known that an age-related hearing loss dominates the high frequency components of speech, in particular the consonant sounds rendering this proposed phrase to repeat extremely difficult for any one with at least a mild-moderate age-related hearing loss. This is consistent with evidence that suggests hearing impairment could be resulting in over-diagnosis of cognitive impairment through biased scores on neuropsychological tools [22], [38].

This hypothesis also takes into account the role central auditory processing may have in the relationship with cognitive decline. Peripheral hearing loss caused by presbycusis is the most common aetiology in hearing impairment, whereas central hearing loss has historically been deemed rare in comparison. There is however, emerging evidence that central hearing loss

could act as a harbinger for the prodromal stages of AD[85].

Peripheral hearing loss is easily diagnosable through pure-tone audiometry[PTA], which is the standardised test for hearing assessment and readily available. Central hearing loss is likely to manifest in more complex dichotic listening tasks, which are not commonly carried out in routine audiology assessments [85]. A dichotic listening task consists of two types of target speech delivered simultaneously to each ear with the listener being asked to repeat either one or both of the target speech material. This task is arguably more realistic to everyday auditory tasks a listener may face in a noisy environment or where there are multiple sources of speech. Studies have suggested that central hearing loss diagnosed through a dichotic listening task may be a pre-cursor to AD and that central hearing screening should be targeted to at-risk groups to identify any potential prodromal AD symptoms [80]

Application of Theory

Both the cognitive loading and social isolation theories could be applied to interventions regarding mid-life hearing loss to delay the onset of cognitive decline.

The most common intervention for hearing loss would be a hearing aid. Figures 2.1 and 2.2 are taken from Uchida et al. [85] and demonstrate how the use of hearing aids may, or in the cases of the common cause and harbinger hypotheses may not, impact on each of the four hypothesis.

Despite improvements in signal processing, Bluetooth connectivity and aesthetics, approximately only 40% of people in the UK who would benefit from hearing aids actually have them [1]. It is also important to note that these hypotheses are unlikely to be mutually exclusive to one another and it is in fact more likely that the true relationship between hearing and cognitive impairment lies within a combination of these hypotheses. Given this and the low uptake of hearing aids, it would seem prudent to investigate other forms of auditory rehabilitation, rather moving importance away from reactive treatments like hearing aids and towards more proactive behaviours to prevent or delay the onset of symptoms.

In Weinstein's update [90] she suggested that it is critical to engage the cognitive reserve in

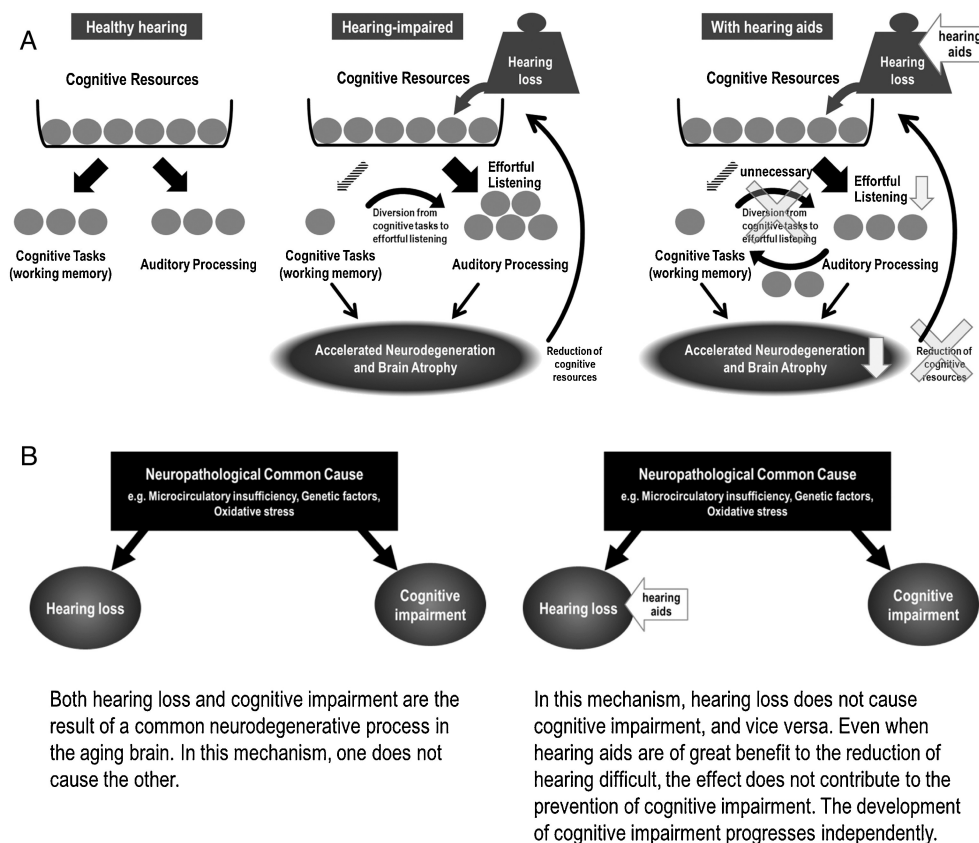
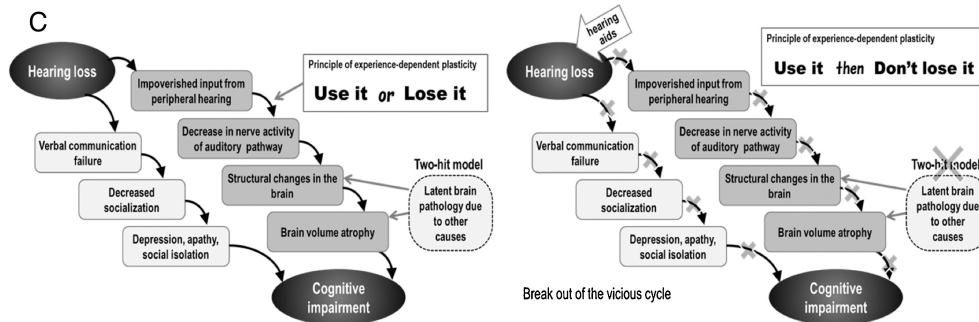


Figure 2.1: Illustration of the cognitive loading hypothesis (A) and the common cause hypothesis (B), with the addition of how the use of hearing aids as a treatment may interact. From Uchida et al [85]



The detriments related to hearing loss can cascade directly or indirectly, leading to cognitive impairment.

When constant input from peripheral hearing is retained with the use of a hearing aid, in accordance with principle of experience-dependent plasticity, the lifelong ability for structural and functional brain reorganization is demonstrated, allowing the brain to adjust to the external or internal environment. Restoring communication ability may help to improve social interactions.

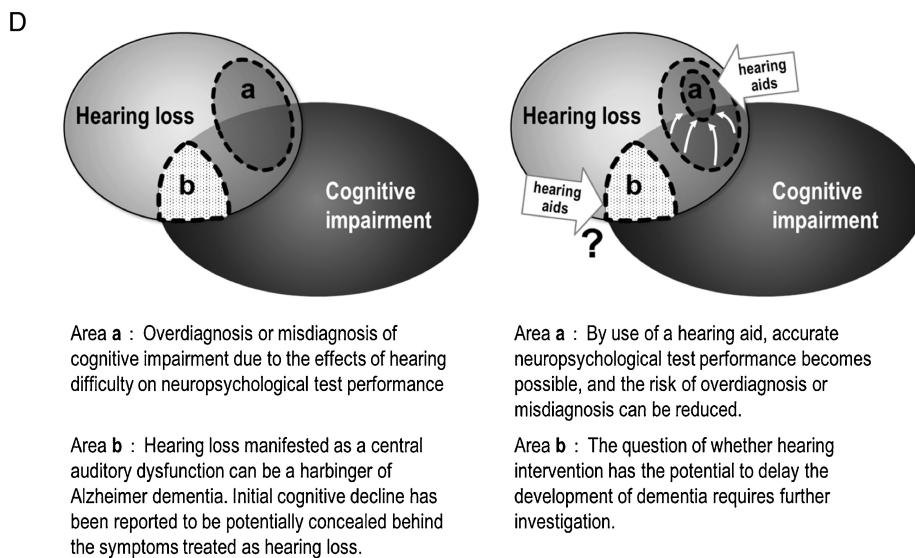


Figure 2.2: Illustration of the cascade hypothesis (C) and the overdiagnosis hypothesis (D), with the addition of how the use of hearing aids as a treatment may interact. From Uchida et al [85]

mid-life, as the less cognitive reserve a person has, the earlier they are likely to develop cognitive impairment and subsequent dementia. Building and enhancing the ‘cognitive resilience’ via intellectual stimulation is important, especially in mid-life as a “window of opportunity” [90]. The better the cognitive resilience, the better the brain copes with damage by using compensatory methods. To enhance the cognitive resilience, she suggests to design interventions to both optimise and maintain social engagement.

Furthermore previous findings from Scarmeas, Levy and Tang et al.[69] reported that participants who engaged in intellectual leisure activities more than six times per week, were 38% less likely to go on to develop dementia. These intellectual activities included playing games. The type of games played are not specified by the authors, but are categorised with playing cards and bingo. It is assumed these may have been board games given the time of publish. In fact the use of games in current dementia research is increasing but in digital formats such as training applications using gamification or serious games.

2.1.2 Serious Games in Dementia Research

Serious games are developed for a purpose other than entertainment, instead the primary purpose of a serious game can be to educate or train the player in fields such as engineering, management and more recently health care [43].

Sea Hero Quest developed by Deutsche Telekom [95], is one example of the growing number of serious games in dementia research. The popularity and accessibility of *Sea Hero Quest* is testament to how the use of a serious game can further the knowledge base identifying risk factors for cognitive decline, with the potential to also act as an intervention for said risk factor.

The application has collected vast amounts of data on what influences spatial navigation in the healthy brain and therefore what indicators of spatial dis-navigation may have on the conditions of the brain, such as dementia.

There has yet to be an application designed to investigate the role hearing loss may have in developing dementia. Given the findings from the Lancet commissions [47] [48] there is a

demonstrable gap in utilizing serious games in hearing loss and dementia.

Using Serious Games to Screen for Cognitive Decline

One concern from the general gaming literature is that older or elderly users may struggle to engage with serious games, due to an unfamiliarity with this medium [29]. Despite this reasonable reservation, an evaluation of a new serious game-based assessment tool for AD [86], reported no usability problems for participants using a touchscreen or joystick without any previous computer experience.

The game produced by Vallejo et al.[86] employed appropriate in-game challenges, prompting and interaction mechanisms to design an effective experience for participants who were older and cognitively impaired. The game included 6 typical daily tasks, determined by the researchers to assess multiple areas of cognitive function. These included: executive function and attention (cooking task); spatial memory (navigational task); episodic memory (shopping for ingredients task). The percentage of success and mean time for task completion was collected for a healthy control group (n=20) and the AD group (n=18).

The MoCA screening tool with a score of above 26 was used to classify participants into the healthy control group. The MoCA has been shown to be a valid, albeit brief, screening tool for mild cognitive impairment [MCI] in participants who would otherwise score over 25 points on the MMSE, in a UK population [72]. The results showed the AD group performed significantly worse in the episodic memory, executive function and attention task compared to the control group, suggesting the game could be used to screen for AD against healthy controls. As this was a pilot study the sample sizes were not adequately powered and the between-group results should be interpreted with caution.

The idea of using serious games to aid early diagnosis of AD was reviewed by Polzer & Gewald [63]. To date, Sea Hero Quest [95] has been the most successful, with approximately 2.7 million downloads at the time of their review. This number has since risen to approximately 4 million downloads at the time of writing. The application is collecting data on navigational

impairments that may appear before memory deficits. Polzer & Gewald [63] concluded that serious games can be utilised to overcome important barriers in the AD diagnosis process, such as delays in self-referral, physician factors, age and available services for assessing cognitive disorders; whilst also acting as a mechanism for early detection in particular areas of health, such as spatial navigational skills. This theory has yet to transition into the role and potential biomarker that hearing loss and subsequent rehabilitation and listening skills may have on early diagnosis of AD and MCI.

Using Serious Games to Improve Cognition

The literature not only suggests that serious games can act as a screening tool for cognitive decline in AD, but also for improving cognitive control in older adults, as documented in the publication Nature [4].

Anguera et al.[4] tested their hypothesis that playing the 3D video game *NeuroRacer* could improve cognition, that had become diminished through healthy ageing. Older adults (n=46) demonstrated less multi-tasking costs when compared to controls over a 4-week period which sustained over a consequent 6-month follow up. Of particular importance is the finding of a ‘*Transfer of Benefit*’. The authors claim that by playing the driving video game, participants demonstrated improvements in both working memory and sustained attention. These were two abilities that were not specifically trained using the video game. Secondly, the authors report that “an increase in midline frontal theta power predicting the training-induced boost in sustained attention and preservation of multitasking improvement six months later.” [4]. This transfer of benefit outside the on-task performance was a novel finding, the authors suggest possible reasoning for this being a) the use of a video game outside of a typical lab environment and b) the custom nature of the video game.

McCallum & Boletsis (2013)[52] conducted a literature review of the use of serious games in dementia populations. They concluded that the preliminary evidence was indeed favourable towards using serious games to train both cognitive and physical functions in those with MCI and AD. The findings by McCallum & Boletsis (2013) [52] and summary by Manera et al.[50] con-

cluded that whilst balance, gait and motor control can be improved by physical fitness games, so too can attention and memory by cognitive games. Additionally, mood and socialisation can also be impacted by both physical and cognitive games.

Meanwhile, there has been less emphasis in the literature on the impact that serious games could have on improving socialisation. This is important to note, as social isolation was identified as a potentially preventable modifier of dementia at 2%, [48] and is known to be associated with hearing loss. In addition there was a lack of qualitative methodology within the general literature surrounding serious games for dementia.

Evidently, according to Polzer & Gewald [63], employing a mixed methods approach would enhance this emerging area of research. Thus it would be prudent to employ a participatory design to involve stakeholders in customising the design of future games and evaluate the results of said game with both validated quantitative measures and qualitative interviews.

The findings from the literature review were piloted further by Manera et al. [50] *Kitchen and Cooking* was designed and evaluated as a serious game to assess the executive function of planning. Different recipes could be played by participants with MCI and AD. The MCI group (n=9) significantly improved over the 4-week period in executive functions, compared to the AD group (n=12) using the Victoria Stroop Test. Yet it is unclear from the results if this improvement would be sustained over a longer period of time, as this pilot study collected data for only 4 weeks across a small sample. The results do lend support to the findings from Vallejo et al.[86], that interventions aimed at training cognitive abilities are more effective for use in a pre-dementia stage. Although, unlike the pilot conducted by Vallejo et al.[86] there was no healthy control group included. It is therefore unclear whether the MCI groups' improvements compared to the AD group would have been any different to a healthy control group.

There was also a large variability in playing time within the small sample size. This again highlights the importance of designing a game that has the capability to both engage and maintain interest for use with the participant group. As shown by the findings by Anguera et al.[4], the success of the study was attributed to the custom design of the game. *Kitchen and Cooking* was

the premise for the design because food was rated as the most interesting area for older people in nursing homes. However, the use of a Participatory design and Agile development [20] would enhance the relevance, challenge and motivation for users to sustain a high level of involvement in the evaluation. Again, a lack of qualitative interviews was cited as a limitation in this pilot study, although self-evaluation questionnaires were used to assess usability and level of interest. Results from these questionnaires demonstrated positive participant experiences pre- and post-training in this particular group of MCI and AD participants.

Despite initial encouraging findings for cognitive training programs used in the pre-dementia stage, such as MCI, robustness of the available evidence is poor. In a systematic review by Butler et al.[10], they concluded that cognitive training can improve domain specific performance in normal cognitive adults, when compared to controls. In contrast there was low-strength evidence to suggest that improved performance is not demonstrated in adults with MCI.

Martin et al. [51] did report better outcomes for participants with both MCI and normal cognition following training, but outcomes did not improve beyond those of the active controls. However, of the 5 MCI studies included there were more limitations than the 6 studies with normal cognitive adults. There were variations in the length of the training interventions, length of follow-up, delivery of intervention, types of control group used and quantitative outcome measures used.

The reliance of quantitative measures in this area of research has been a criticism. One study that has used a qualitative methodology is that of Talaei-Khoei & Daniel [81]. They investigated older adults' perceptions towards using video games, in this instance the Xbox Kinect *Dr. Kawashima's Brain Training*, as a way to maintain their cognition through intellectual exercise. As mentioned previously, the design of the games should be appropriate to engage a specific population to benefit and Talaei-Khoei & Daniel [81] attribute this to a *Perceived Transfer Effect*.

Anguera et al. [4] suggested that transfer of benefit occurred by use of a 3D driving video game. Whereas Talaei-Khoei & Daniel (2018)[81] take a slightly different view by suggesting that adults who see a cognitive game as empowering rather than supportive can provide

long-term benefits. A key finding was that the cognitive training game was perceived to be useful in maintaining cognition and transferring that cognition to daily tasks, such as reading. Participants (n=21) felt by sustaining function, through the games, they would be able to live independently for longer.

Although these results do not particularly lend support to the use of video games in delaying cognitive decline, they do offer rich data from intended user groups. The lack of qualitative data in this field, may be why other serious games studies, such as those reviewed by Martin et al. [51] have yet to yield evidence of high quality to support the use of serious games in MCI populations.

Other key findings from the qualitative study distinguish perceptions of supportive and empowering technologies. For instance, the use of hearing aids is categorised as supportive. Hearing instruments can only aid a person in a functional ability that has already begun to decline. This could lead hearing aids to be perceived as less useful, particularly in the long-term. Whereas, a video game that was empowering could be perceived to have long-term effects on cognitive ability that are then transferable to daily functioning.

Participants felt that *Dr. Kawashima's Brain Training* would be helpful for speed processing, attention and memory. This was then perceived to transfer into helping them in conversations and taking medicines. Whilst some participants found the game confusing, they also found it fun and were motivated to improve their memory age – a measure of achievement and reward with the game. Furthermore, participants suggested the game would be more enjoyable and motivational if there was a social aspect, such as a platform for social interaction and recommendations by friends. The authors also concluded that more qualitative research is required in the field, specifically on why end users would think a training game would be useful and adopted. Certainly, the use of a participatory design with a specific stakeholder engagement session would have the ability to investigate that question further.

Although the perceived transfer of benefit from cognitive training games has not been evaluated, the results from Talaei-Khoei & Daniel[81] suggest that using games with socially interactive elements would be favoured by older adults and could be seen as more beneficial in the long-

term than hearing aids. As social isolation is associated with hearing loss and documented as a potentially modifiable risk factor in developing dementia [48], using a serious game to also improve socialisation could be important in preventing cognitive decline.

2.1.3 Auditory Training in Rehabilitation

Prior to the initial Lancet finding[48], that hearing loss and social isolation are potentially modifiable risk factors in dementia, research into the role of auditory training on cognition was also attracting interest.

It is well known that hearing aids can improve speech audibility and restore awareness of sound, however the ability to listen to and understand speech may still be poor. The uptake and use of hearing aids is also relatively low, in comparison to those who would indeed benefit from regularly wearing hearing aids. It is thought that hearing aids alone, cannot fully improve speech understanding, especially in environments when the signal-to-noise ratio [SNR] is poor. Social situations such as restaurants, parties and group conversations are common examples of poor SNRs and require other listening tactics to be employed to understand the speech signal. These tactics may be auditory and include assistive listening devices, such as remote microphones, or non-auditory, such as lip-reading or optimal positioning in the room. Another alternative tactic is to improve one's ability to comprehend speech and improve listening in noise by completing an auditory training program.

An auditory training program generally consists of listening tasks ranging from easy to advanced, using an adaptive approach to set the difficulty of the task. Computer-based auditory training has shown to be both time and cost-effective. There is a low-barrier entry to the training packages, as they are available online or through downloading an application onto a smartphone or tablet. Examples include Listening and Communication Enhancement [LACE][76] and Hear Coach [82].

Castiglione et al. [13] reviewed audiological and cognitive evaluations for patients over 65 years old with hearing loss (n=105) and normal hearing (n=20) before and after undergoing audio-

logical rehabilitation. This included fitting of hearing aids and auditory training. Participants were divided into 6 groups depending on the severity of their hearing impairment. All groups showed post-rehabilitation improvement for both short and long-term memory tasks, cognitive scores and depression. These findings support the cognitive loading theory, as the restoration of listening skills through hearing aids or auditory training could effectively re-allocate the resources again. An alternative suggestion for the improvement following rehabilitation could be that auditory training enhances working memory, self-efficacy and self-motivation, any or all of which could result in better cognitive performance. These findings would support the perceived transfer effect proposed by Talaei-Khoei & Daniel [81]; however the placebo effect cannot be discounted.

Such positive findings have not been replicated in other studies evaluating auditory training. A systematic review of the evidence on computer-based auditory training packages demonstrated an improvement only in the on-task activities within the training packages. This improvement was not seen in off-task activities in real world listening environments. Despite this, some studies have shown improvements in auditory working memory, attention and comprehension following auditory training. This warranted further investigation on the importance of cognition in listening to speech [32].

In a follow-up study, Ferguson et al.[24] conducted a RCT to evaluate a phoneme discrimination training program for hearing and cognitive functions. As in the systematic review, there were significant training improvements in the complex cognitive tasks, such as divided attention, which were sustained at 4-weeks post-training. Moreover, there was robust on-task learning for the training material, concurring with the previous literature, but a lack of off-task improvements in speech recognition. One reason for this lack of off-task improvement could be attributed to compliance and motivation. Auditory training compliance rates are variable, for instance Sweetow & Henderson Sabes [78] only reported 30% compliance with the LACE package in a clinical population in the United States. However, in Ferguson et al.[24] compliance was high at 80% from a sample size of 44.

Another possibility for a lack of off-task improvements for speech perception may be the out-

come measures used. Similarly, reported in the systematic review by Martin et al. [51], the choice of outcome measures used in auditory training studies is varied. The Digit Triplet Test used by Ferguson et al. [24] may not have been sensitive enough to detect small changes in performance, as it contains only nine speech stimuli, especially with a sample of participants with mild hearing loss. Using a more realistic and phonetically variable test like the QuickSIN [40] may be more sensitive in detecting changes in speech perception. The QuickSIN has been shown to yield the largest effect sizes from the literature [78].

Ferguson et al. [24] overall conclusion was that phoneme discrimination training did provide some benefit for listening and complex abilities required in realistic environments. Nevertheless, the training was a basic adaptive phoneme detection task which provided users with feedback of correct or incorrect. The perceived transfer of benefit for the auditory training may not have been recognised by the participants, due to a low level of interactivity and/or motivation. Although delivered at home, the nature of the phoneme training task still resembled the lab-based environment test, which Anguera et al.[4] suggested as a reason for yielding poor off-task improvements. There is an argument that embedding the training in a serious game could overcome these issues. There was also no inclusion of socialisation within the phoneme training game, when it's purpose was to improve speech perception in socially complex environments. There is also scope to investigate this element further by introducing competition into a serious training game.

The literature shows that gamification can provide a platform to offer customised, home-based training for different areas of health behaviour change, including cognitive performance. Previous studies have demonstrated that certain games have the potential to transfer benefits of virtual play into self-confidence in maintaining cognitive effort for daily activities. More specifically, utilising training games that are deemed as useful and engaging to users in a pre-dementia stage may be more effective than after a dementia diagnosis. Given the findings from Livingston et al. [48] there is a demonstrable gap in utilising games to investigate age-related hearing loss and cognitive decline. There has yet to be an application that has been iteratively designed using qualitative input from key stakeholders to investigate the role of hearing loss and speech perception in cognitive impairment. The use of participatory design with a specific stakeholder

engagement would have the ability to investigate this area further.

The overall aim of this thesis is to investigate whether a serious game can be developed to improve speech perceptions in noise and attentional performance in a mid-life population at risk of presbycusis and mild cognitive impairment.

In order to achieve the aims there will be two separate stages:

Stage 1: To adopt a Participatory design approach with relevant stakeholders to produce a training application that has been iteratively designed to provide auditory-cognitive training via smartphone or tablet.

Stage 2: To evaluate the application in a population likely to be affected by mild hearing loss and potentially cognitive decline, and assess whether prolonged training can yield improvements in attention, listening and quality of life.

Chapter 3

Stage 1: Participatory Design

To ensure that the auditory-cognitive training application was relevant to its intended users, a participatory design approach was employed. This comprised of two cycles of design using a combination of focus groups and paired semi-structured interviews to test out a number of design elements that had initially been based around the literature. This chapter describes how the participatory design phase was conducted, the findings and how this led to the development of a alpha-version of the application that became known as HELIX.

This chapter has been adapted from a published peer-reviewed journal article that was published in 2020 [27]. Permission from the publisher has been granted and is included in the appendices.

Abstract

Multiple gaming applications under the dementia umbrella for skills such as navigation exist, but there has yet to be an application designed specifically to investigate the role hearing loss may have in the process of cognitive decline. There is a demonstrable gap in utilising games to further the knowledge of the potential relationship between hearing loss and dementia. The aim of this study was to identify the needs, facilitators and barriers in designing a novel auditory-cognitive training gaming application. A participatory design approach was used to engage key stakeholders across audiology and cognitive disorders specialisms. Two rounds, including paired semi-structured interviews and focus groups were completed and thematically analysed.

18 stakeholders participated in total and 6 themes were identified to inform the next stage of the application’s development. The findings were implemented into the development of the application ready for evaluation.

3.1 Background Research

There is currently no treatment available to either cure or prevent dementia, which has led the WHO to classify dementia as a public health priority [93]. The call to action is to reduce the risk of developing dementia through early diagnosis of cognitive decline, intervention and eventually prevention.

The evidence published in The Lancet reviews [47, 48] concurs with previous research suggesting that age-related hearing loss (presbycusis), increases the risk of developing dementia in later life by up to 5 times [45]. Despite these findings, the causality in this relationship is still unknown. As is whether any form of rehabilitation, either through hearing aids, auditory training, or assistive listening devices, could delay or prevent the onset of dementia symptoms [48].

The most robust methodology to further investigate this relationship would be an adequately powered, longitudinal, RCT. A complex study such as this would need to ensure any treatments, such as hearing aids, were adhered to throughout the study. The adoption and use of hearing aids is known to be relatively low. In the age bracket of 55-74 years old, 80% of those people who require hearing aids do not own them [53]. This would be a key issue to address in the design of such a trial. Other methodologies should therefore be explored and, as hearing loss in mid-life could be a preventable factor, the focus, as outlined by the WHO, should be early detection and intervention. Cohort studies have suggested presbycusis tends to precede dementia onset by 5-10 years [49]. Interestingly on average people tend to wait 10 years before they seek help for their hearing [16]. Diagnosing hearing loss is a simple, quick, diagnostic test and an easily measurable critical factor in potentially preventing cognitive impairment.

This work therefore highlights an under-researched group of people who may be in the early

stages of presbycusis and present with a mild to moderate hearing loss, do not seek treatment, but have an increased risk of developing dementia. There is potential to investigate these ‘pre-clinical symptoms’ of dementia in this group by targeting areas of the brain that contribute to auditory and cognitive function, with the possibility of delaying the onset of said symptoms. This area of research has the potential to impact upon one of the largest healthcare issues of the next century.

3.1.1 Gamification in Dementia Research

One potentially more achievable alternative to a RCT is to engage people in preventing dementia symptoms through gamification. Gamification has been shown to be an effective research tool that can demonstrate and maintain health behaviour change [23]. The use of a gamified application would be highly accessible within the home environment and provide less of a barrier than seeking primary care treatment for initial changes in cognition.

A literature review of games aiding early diagnosis of dementia and particularly AD [63] concluded that games could be utilised to overcome important barriers in the diagnosis process. Delays in self-referral, physician factors, age and available services for assessing cognitive disorders were all identified as potential obstacles. A gaming application could be more motivational compared to a written memory assessment, whilst also maintaining a low cost/high reward, if evidence demonstrated that the application could delay or prevent the onset of dementia symptoms.

A further potentially significant factor in using a customised gaming approach is the theory of *Transfer of Benefit* posited by Anguera et al [4]. This concept that a game could provide benefits in functions not necessarily targetted by the game itself. In this particular study, improvements were seen in working memory and sustained attention in the training group (n=46) compared to the control group after playing a driving video game. With suggested reasoning for the improvement being access to the game outside of a typical test environment and the customised nature of the game. At the time of writing there has been no attempt to address hearing loss and impaired speech perception using such an approach.

A second customised game worth noting is *Kitchen and Cooking* [50]. Based around cooking different recipes to assess the executive function of planning, the game was piloted in a sample of participants with MCI and AD. Although the sample size was small, the MCI group (n=9), demonstrated significant improvements over the 4-week testing period on the Stroop Test, in comparison to the AD group. Whilst there is no evidence to suggest if this improvement would be sustainable over a longer period of time, the results do suggest that targetting improvements in executive functioning, in this case planning, are more likely to be effective for those in earlier stages of cognitive decline.

As suggested by Anguera et al. [4] the success of *NeuroRacer*, was attributed to the custom design of the game. Whereas in *Kitchen and Cooking* the premise for the design was because food was rated as the most interesting area for older people in nursing homes. Thus, it would be prudent to employ a participatory design to involve key stakeholders in customising the design of future games and evaluate the results of said game with both validated quantitative measures and qualitative interviews.

One study that did utilise qualitative methodology investigated older adults' perceptions of playing the Xbox Kinect game *Dr. Kawashima's Brain Training*, as a way to maintain their cognition through intellectual exercise [81]. As previously suggested to ensure a game is successfully adopted by the intended user group, the design should be appropriate to engage said specific population to benefit. Talaei-Khoei & Daniel [81] attribute this to a *Perceived Transfer Effect*.

This occurs when adults who see a cognitive game as empowering, rather than supportive, so equates to a higher potential to yield long-term benefits. Rather it is not only the content of the game, but how participants view said content in respect to their own selves. A key finding was that the mini-games in *Dr. Kawashima's Brain Training* were perceived to be useful in maintaining cognition and transference to real-world daily tasks, such as reading. Participants (n=21) felt by sustaining function, through the mini-games, they would be able to live independently for longer providing long-term transfer of benefit.

Other key findings distinguish perceptions of supportive and empowering technologies. For

instance, the use of hearing aids is categorised as supportive. Hearing instruments can only aid a person in a functional ability that has already begun to decline. This could lead hearing aids to be perceived as less useful, particularly in the long-term. Whereas, an empowering virtual game focusing on active auditory training could be perceived to have transferable long-term effects on cognitive ability.

These findings from Talaei-Khoei & Daniel [81], can be better explained using the self-determination theory, which suggests that people are most motivated when their basic psychological needs are met. These are autonomy, competence and relatedness [66, 67]. Hearing aids could be seen as imposed externally, by a clinician or through pressure from family members which would likely reduce autonomy. The stigma of wearing hearing aids and connotations with ageing, could reduce an individuals' relatedness to peers or family. Whilst the process of using something new and different, could challenge confidence. Wearing hearing aids has the potential to invalidate all three elements of the self-determination theory framework. Whereas an auditory-cognitive training application could offer a sense of mastery, through structured challenge and measured improvement fostering competence. Autonomy would be satisfied through choice and control of session length and customisation supporting a sense of ownership. Whilst a game that enables the sharing of progress such as leaderboards and scores connects users to others with similar goals, strengthening relatedness through social connection. The authors also concluded that more qualitative research is required in the field, specifically on why end users would think a training game would be useful and adopted.

The literature shows that gamification can provide a platform to offer customised, home-based training for different areas of health behaviour change, including cognitive performance. Previous studies have demonstrated that certain games have the potential to transfer benefits of virtual play into self-confidence in maintaining cognitive effort for daily activities. More specifically, utilising training games that are deemed as useful and engaging to users in a pre-dementia stage may be more effective than after a dementia diagnosis. Given the findings from Livingston et al. [48] there is a demonstrable gap in utilising games to investigate age-related hearing loss and cognitive decline. There has yet to be an application that has been iteratively designed using qualitative input from key stakeholders to investigate the role of hearing loss and speech

perception in cognitive impairment. The use of participatory design with a specific stakeholder engagement would have the ability to investigate this area further.

3.2 Aims and Objectives

The overall aim was to therefore investigate whether an empowering gaming application could be designed to engage users in a mid-life population at risk of presbycusis and mild or subjective cognitive impairment to improve speech perception and cognitive performance. This aim will be achieved with the following objectives:

- To adopt a participatory design approach with relevant stakeholders to produce an auditory-cognitive training application that has been iteratively designed.
- To understand facilitators and barriers to producing an auditory-cognitive training application.
- To identify the specific design requirements for an auditory-cognitive training application.

3.3 Methods

3.3.1 Participants

18 relevant stakeholders (service users, clinicians, researchers) were recruited across audiology and cognitive disorder clinics at Imperial College Healthcare; across research groups at Imperial College London and their corresponding research networks. Participants were chosen using an opportunity sampling method as it was a convenient way of accessing clinical, service user and researcher expertise. Participants were included in this study if they were considered to be a stakeholder and had capacity to provide informed written consent. Professionals were considered key stakeholders by the research team if they had experience with patients and families at risk of either presbycusis and/or mild or subjective cognitive impairment. Service

users were considered key stakeholders by the research team if they or family members reported mild hearing loss or mild or subjective cognitive impairment.

As the application will be designed for those who may report mild or subjective cognitive impairment, it would not have been appropriate to recruit service users with a moderate to severe cognitive impairment. Therefore, potential participants who already had a medical diagnosis of dementia were not considered. Decisions for stakeholder inclusion were taken by the research team to ensure the participants were representative of the desired end user of the final application. Table 3.1 describes the type of stakeholders recruited and when they participated in detail. This study was approved by the West Midlands – South Birmingham Research Ethics Committee (Reference number 18/WM/0261). All interviews and focus groups were carried out at Imperial College Healthcare Trust, audio-recorded using a Zoom Q8 and transcribed verbatim.

Type of Stakeholder	C1-Interview (<i>n</i> = 4)	C1-FG1 (<i>n</i> = 5)	C2-FG1 (<i>n</i> = 5)	C2-FG2 (<i>n</i> = 5)	C2-FG3 (<i>n</i> = 4)	Total (<i>n</i> = 23) ¹
Service User	3		5	3		11
<i>Audiology</i>	2		5	2		9
<i>Cognitive Disorder</i>	1*			1*		2
Spouse	1**			1**		2
Volunteer				1***		1
Clinician		4			3	7
<i>Audiologist</i>		3			3	6
<i>Older Adult Psychiatrist</i>		1				1
Researcher		1			1	2
<i>Dementia Research Nurse</i>		1				1
<i>PhD Researcher</i>					1	1

Table 3.1: Description of Stakeholders

Notes:

*This participant is primarily a service user of the cognitive disorders clinic, but has also used audiology services.

**This participant was recruited as a spouse of a service user, but has also used audiology services for themselves.

***This participant is a volunteer in audiology, but also has a hearing loss.

¹ A total of 23 participants took part across the two cycles, but 5 stakeholders participated in both cycles.

A summary of the data collection, including start and stop dates, duration of each cycle and stakeholder participation can be found in Figure 3.1.

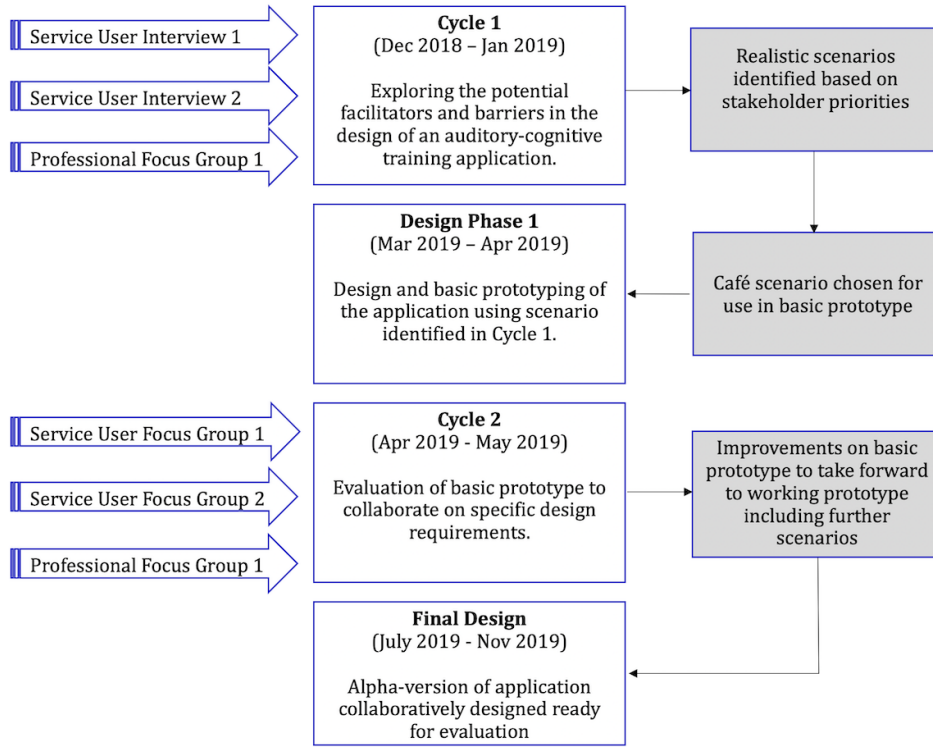


Figure 3.1: Overview of each interaction during the participatory design phase, relevant actions and outputs.

3.3.2 Data Collection

Cycle 1: Identifying the current climate

The aim of the first cycle of data collection was to first gather knowledge about the potential facilitators and barriers in designing a novel auditory-cognitive training application. To maximise accessibility of the data, the first round of data collection consisted of two paired semi-structured interviews for service users and a focus group of 5 professional stakeholders, which were 45 minutes and 60 minutes respectively. This division of the stakeholder groups was beneficial for various reasons. The use of the focus group allowed discussion of professional opinion and fostered further collective thinking. Whereas interviewing service users in pairs allowed the interviewer to explore personal experiences and views in depth by comparing and contrasting. The topic guides used for both the interviews and focus groups are available in the appendices. The exploratory nature of cycle 1 allowed the data collected to be analysed and used in conjunction with the literature base to design the first version of the application.

Further evaluation of this first version was then explored in cycle 2.

Cycle 2: Exploring specific requirements and needs for collaborative design

The purpose of including a second cycle was to demonstrate the initial version of the application and to stimulate participants into further thinking about the specific needs and requirements of the application. In order to achieve the objectives of cycle 2 and answer a more specific research question about the application design, an edited topic guide was used for both the professional and non-professional focus groups, which were approximately 60 minutes in duration. Topic guides can be found in the appendices.

2 service users, 1 spouse and 2 professional participants who wished to continue into cycle 2 participated alongside 9 new participants who did not have any prior involvement or knowledge of the application. A basic prototype of the application was demonstrated using an iPad with a coffee shop scenario, in which the player was asked to listen to an order placed in the coffee shop, choose the correct customer order that was heard, then choose the correct items from a list of 8 images/words to make up that specific order. The audio was originally played at a low SNR, which the player could improve by 2 dB at a time by replaying the order before moving on to choosing what had been heard from a 4-option list. Screenshots from the prototype demonstrated in cycle 2 can be seen in Figure 3.2.

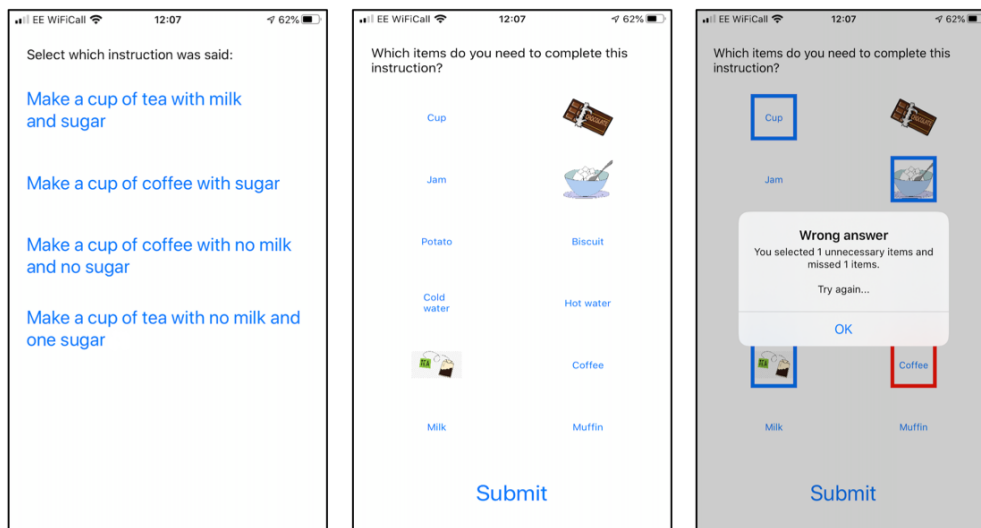


Figure 3.2: Selection of screenshots from the initial application development.

Data Processing

Audio recordings from the interviews and focus groups were transferred immediately to an encrypted PC and deleted from the audio recorder. The recordings were transcribed by the lead author in cycle 1 and by medical students, who had received prior training, in cycle 2. The transcriptions were subsequently coded by the lead author in cycle 1 and medical students in cycle 2 and stored in Microsoft Excel. To verify the integrity of the data, each cycle was secondary coded by either the lead author or medical students. All excerpts from the transcriptions were anonymized using the participant number that identified each participant only as either a service user or professional.

Data Analysis

A thematic analysis was conducted using Braun & Clarke's six phase approach [7] to identify themes from the data related to the facilitators, barriers and needs of the stakeholders in developing a new auditory-training gaming application. This process involved reading and reviewing the transcripts to familiarise the dataset. Initial codes were generated inductively from the data by the lead author and three medical students, who had received training in thematic analysis. This was completed independently for a subset of the data, which was then refined into a coding framework and utilised for the remaining data. Codes were then collated into potential themes and iteratively reviewed before the final report of data analysis.

3.4 Results & Discussion

Six themes were identified from the focus groups in relation to the needs, barriers and facilitators in developing an auditory-cognitive application that would be useful, fun and accessible. The themes are (1) Congruence with hobbies (2) Life gets in the way (3) Motivational challenge (4) Accessibility (5) Addictive competition (6) Realism.

Congruence with hobbies

Throughout the focus groups, the service users commented particularly on what would continue to motivate them to play the game across an extended period of time, rather than a one-off use. At first it appeared to be different styles or themes of games that motivated them, such as word games or online chess. However further discussion by two service users who were not regularly playing mobile games led to the consensus that if the theme of the game was an extension of an enjoyable hobby then this would heavily facilitate not just initial interest, but extended and continued playing time.

‘I mean this game is educational but you want to make it fun as well, fun at the same time.’[SU9]

‘For example if you had one about art?’ [SU8]

‘Yes, I’d use it.’ [SU9]

‘You’d be at it all day!’[SU8]

Life gets in the way

Whilst both service users and clinicians agreed that the premise of the application was a good idea, the issue of finding the time to use the application was raised as a potential barrier. In practical terms it was suggested that the user would need to be at home in a quiet space to be able to use headphones and concentrate. Others suggested that busy lives meant other responsibilities, such as taking care of grandchildren or house chores take priority over self-care. This feeling of being too busy to use the application draws parallel with reactive or passive healthcare, such as using hearing aids when a hearing loss has been diagnosed, as opposed to a preventative or active approach, whereby spending a small proportion of time each day may in fact benefit in the longer-term.

‘I find that I don’t pick up my iPad and read the paper anymore, I didn’t realise I didn’t do it. But then when I went to my iPad it had no battery and I didn’t care,

so it was kind of like oh I've stopped reading the paper, but I didn't really notice. And now I think about it, my sister had melanoma and that was kind of difficult so I've stopped reading and haven't picked it up again.' [SU10]

'I'm also quite involved in the church, and the grandchildren. So I think when you are saying as to what might prevent you from doing these other pleasurable things, then it would be other equally pleasurable things that one has to do.' [SU8]

Using notifications and reminders within the application was suggested to remind users that they were overdue a training session. Or to use commuting time on the underground or train as an opportunity to play. Interestingly in the professional group there was a misalignment in views regarding whether people in an older age group would engage with smartphones and headphones whilst travelling.

'I don't think I've seen anyone like in their sixties even [using a smartphone?].'
[P1]

'I have.' [P2]

'Have you been on the tube?! I think they do!' [P3]

'I could probably play it on the bus or something you know, when you are travelling, something to just fill time.' [SU7]

'Yes on the tube.' [SU10]

Motivational challenge

Despite the issue of needing to set aside time to play each day, a main facilitator identified from both the service user and clinician groups was that the application must provide the right level or personal motivation and element of challenge to ensure it was fun, useful and enticed the user back to play. Participants described their own ideas of what motivation may feel like in line with the motivation continuum [66]. The motivation continuum is important to review

as it describes motivation, not just as external against internal, but how a user's actions in utilising the training may be influenced by their own choices and values versus other external pressures.

For instance, the motivation did not necessarily need to come from improving one's own prowess. The idea of altruism being a motivator was discussed. It was suggested that if a person was aware that playing the application would be contributing to the research knowledge on dementia, they would be much more likely to play it as it may not necessarily gratify them personally in the short-term. The professional group suggested that using multiple scenarios would increase the relevance to challenges faced by hearing impaired people and therefore increase the motivation to improve in all situations.

'For me I would be more encouraged if I knew it was paying back into research. If I knew that somebody thought it was good for me too. If I was playing it just for the sake of playing it then I would be playing it for nothing. But if I'm playing it and I'm contributing then I can pretend I'm contributing even if I'm just playing for myself.' [SU10]

'It would be good if they can select what do you want to train. I had the problem the other day speaking with my friend at the Café...Maybe I'll give it a go, yes today I'll play the Café.' [P19]

'It's motivation as well, because if you do terribly at the one in the Café but you're doing fantastic at all the others. I am going to the do that Café one again, I am going to smash the Café one today.' [P1]

Accessibility

One clear need highlighted from both cycles was that the application needed to be accessible for all ages, catering for those with visual or audio impairments and available to play on appropriate platforms. Using appropriate screen resolutions, font sizes, images and colours were

all design parameters that were identified as important.

‘I have been testing patients as well, elderly patients for my study and I use an app on the iPad as well as computer tasks and they tolerate it very well. They never complain when I say lets switch it to the iPad, actually they like the one on the iPad more.’ [P19]

‘I think most people are going to play for that age on a phone or an iPad. I think it would need to go across both platforms because what is it 25% Apple, 75% Android?’ [SU3]

‘If I could do it via the computer...um simply I’m used to using the computer.’ [SU8]

‘I think the size is relevant actually, that tiny screen it [of a smartphone] it’s not quite the same as if you were looking on the screen.’[SU9]

Addictive competition

Comparing the premise of this application to other successful games that the participants played resulted in agreement as to why people went back to playing certain games repeatedly, and over a long period of time. The applications or games that achieved sustained engagement elicited repeat play through satisfying experiences. This was not only achieving the aim of the games themselves, but also the competitive nature of moving through levels to beat a family member, partner or friend. Having a shared platform to engage in healthy competition was seen as a driver for playing an application. Using scores, rewards and trophies were all seen as additional extras that would provide extra facilitation in prolonged and repetitive play. This draws parallels with findings from Ryan, Rigby & Przybylski [67], who proposed that human motivation tends to be driven by three basic psychological needs. These are competency,

autonomy and relatedness. They suggest that using video games often provide a platform to nourish these needs, hence they become motivational to play and users tend to return for these satisfactory experiences.

‘Maybe I could compare this with my husband or my friends and then I would know they were able to do it like three tones before me, so maybe I am actually a bit worse.’ [P19]

‘Another way that I’ve mentioned might be to pair up with a relative or have some kind of competitive nature you know in the household.’ [P5]

‘My mother-in-law could see my scores if that was of interest to her.’ [SU10]

‘Competition, no?’ [SU7]

‘Gives you more motivation I think, if you’re in a competitive nature.’[SU13]

Realism

The application in cycle 2 was demonstrated using a coffee shop scenario, which received positive feedback from all participants as it involved a real-world environment, where it was likely that a person may have difficulty hearing speech. All participants agreed that it would be most appropriate to use ‘real-life’ scenarios in the game, instead of complete gamification. It was suggested that using realistic scenarios would make the application more useful and the skills built in the game more transferable. It was suggested that using realistic tasks would also make the game more appealing to an older person, as it made it feel less like a game. The clinician group felt that using these scenarios would also make it easier for them to recommend the game and also to use the game to obtain feedback about specific situations that the person was having particular difficulties with. By being realistic the game would also tie in with the theme of using hobbies as scenarios.

‘It has to cover areas that a person like myself would find it very difficult to hear,

like for instance I said the gym, but also airports they can be a nightmare as well, you know I still have to travel even if I'm deaf.' [SU13]

'Particularly if they are already isolated and they're already staying at home and they're sort of scared of going outside, it's a nice way to bring outside in, so they can build up their experience in other situations without actually having to get there.' [P3]

'And it's an element of control that they're taking over their situation and so that it'll give me some confidence you know I'm doing something about it. Makes you feel good.'[P1]

This study aimed to engage relevant stakeholders from the worlds of audiology and cognitive disorders to collaborate in the design and development of an auditory-cognitive training game application. Stakeholders were recruited and engaged in two cycles of semi-structured paired interviews and focus groups to understand the facilitators and barriers in producing such an application and to elicit specific design requirements for the application in addition to the current literature.

3.4.1 Facilitators

A popular choice for facilitating a new gaming application was for it to provide a high level of addictive competition for the user. The results demonstrate that this can be achieved through a number of ways including rewards, achievements and competitive play with family and friends. This draws parallel with the findings from Talaei-Khoei & Daniel [81], who found that their participants were motivated to improve their memory age as it provided them with a sense of achievement and reward. This study also found that participants wanted an extra level of socialisation within the application through a virtual competition with friends to share scores and achievements.

Theme	Facilitators	Barriers	Needs
Congruence with hobbies	Initiate and maintain interest over time to allow repeated play. Concentrate on being educational and enjoyable	Limitation of number of pre-programmed scenarios to cater for all hobbies	Relate to common enjoyable hobbies for the intended user groups
Life gets in the way	Promote using the app during unavoidable daily tasks e.g commuting	Incorporating the app into busy daily lives. Reliance on passive healthcare models	App to send notifications and reminders when the user is overdue a training session. Allow offline play e.g when commuting
Motivational challenge	Promoting altruism to contribute to research	App not offering the right level of, or type of challenge leading to a lack of repeated play/training	Level of difficulty to be challenging enough to entice repeated play. Multiple scenarios relevant to difficult hearing situations
Accessibility	Design considerations e.g use of colours, font, sizes and images	Smaller screens on smartphones. Inappropriate screen resolution for each device	Accessible to all ages. Available on multiple platforms and devices including PC
Addictive competition	Option to share progress with family and friends to encourage competition	Not a driver to play for people who are not of a competitive nature	Include daily high scores that are comparable to friends or self across time
Realism	Skills honed in the app would be more transferable. More likely to recommend to friends	May prefer more realistic graphics rather than taking a gamified approach	Relatable to true to life environments where hearing is difficult

Table 3.2: Summary of findings in relation to the Stage 1 research question

This sharing of information was also addressed in ensuring the application was motivationally challenging enough to encourage them back to play. A particularly interesting finding was that the motivation to play the application was not necessarily to improve one’s own skills, or for personal gain, but to provide data altruistically to a research database on a topic such as dementia. This draws parallel with the popularity of Sea Hero Quest developed by Deutsche Telekom, which has been downloaded by over 4.3 million players at the time of writing [95]. Sea Hero Quest is an application developed to collect large data sets on how navigational cognition changes over the human life span. Collecting data through game-play has provided data that

would have taken 176 centuries to obtain through standard dementia research practices.

3.4.2 Barriers

One of the themes that was perceived as a barrier to producing a successful application for high adoption was that other life activities would get in the way of using the application on a regular basis, as it would require a quiet space to concentrate. Participants gave examples of other activities that required their attention and efforts that were placed above auditory-cognitive training, such as household chores. The low level of importance placed on maintaining cognitive reserve in light of other daily activities by participants is in contrast to the theory of Weinstein [90], who suggests the building of cognitive resilience is of utmost importance in the window of opportunity that is mid-life. It is critical to engage the cognitive reserve in mid-life to allow the brain to cope better with damage in later life.

The findings from this study demonstrate that even with this knowledge, changing health behaviours is a challenge and often unsuccessful [39]. It is therefore critical to follow the proposals from Talaei-Khoei & Daniel [81] and employ qualitative methods, as in this present study, to focus specifically on why end users would find a training game to be useful and adopt it.

One potential barrier to using hobbies as a motivator is the effect of apathy on motivation. Apathy is a major neuropsychiatric symptom in dementia, and is sometimes observed in MCI patients [57]. Individuals with clinical apathy would be less likely to be motivated by the type of training described. However, it should be noted that the intended user group is specifically focused on individuals with subjective cognitive impairment and MCI, who have a much lower incidence of apathy than those with more severe cognitive impairment [60].

3.4.3 Needs

One of the specific requirements that was elicited from the discussion was to ensure that the application was accessible for older adults, who may be unfamiliar with using tablets or smart-

phones to access applications. This is also a potential barrier raised in the general gaming literature; however, in Vallejo et al.[86] there were no usability problems reported for participants without previous computer experience when using a joystick or touchscreen.

Interestingly participants felt that making the scenarios more realistic to daily living would be more useful, transferable and more appealing to older adults by making it less gamified. Results showed that if the scenarios were congruent with or an extension of an enjoyable hobby for the end user, this would increase the level of interest, fun and ultimately adoption. This finding could provide reasoning for why laboratory-style auditory training programs, such as those evaluated by Henshaw & Ferguson [32] have failed to extrapolate on-task learning to off-task daily activities. As suggested by Anguera et al. [4] their training game was successful due to being delivered outside of the laboratory environment and its custom design. Similarly, the reason Manera et al. [50] found large variations in playing time in their application based around cooking may be due to the design lacking engagement and interest for their particular end user group. Therefore, the use of multiple common scenarios based around daily activities and a custom scenario based on a hobby may in fact increase adoption and success rate outside of the application.

3.4.4 Limitations

The use of a small sample size is more common in participatory design, as it is about the rich quality of the data rather than the quantity. Demographically, the age range and use of hearing aids was skewed from the desired end user group. However, it allowed exploration of using this type of application as a supplement to hearing aid provision in more severe hearing losses in the future. As this application is in its infancy and has yet to be evaluated to see its effectiveness – there is potential to use the application in other, more hearing-impaired populations. However, for the scope of this project, involving those with varying hearing loss severities would introduce a confounding variable when assessing if using the application does indeed improve un-aided speech listening in noise.

3.4.5 Lessons Learned

Stakeholder Recruitment

The inclusion of non-clinical stakeholders that already have existing relationships can enhance data collection. In both cycles the stakeholders included spouses and friends. This extended the depth of data collection around more sensitive questions, such as thoughts and feelings about developing cognitive impairment and current cognitive performance. Stakeholders were more comfortable discussing these issues with someone they already knew, as opposed to the interviewer. This was observed in a similar design workshop with aphasia patients [41]. The author concluded that using a relative is essential in fostering a ‘communication culture’, which gives the stakeholder with the condition confidence to express and verbalise their thoughts and feelings.

It was also useful in stimulating further discussion as the stakeholders had more background information about each other in comparison with the interviewer. Stakeholders were able to ask further appropriate probing questions when discussing content. This was evident when discussing possible scenarios for the gaming levels, as one stakeholder was able to talk more to their spouse about their enjoyment of art galleries and bring this idea to the discussion.

When holding clinical stakeholder focus groups, a multi-disciplinary discussion should be used to uncover shared thinking that provides not only useful data for answering the research question, but also to take further into wider clinical practice outside of the application design. In this instance mixing clinicians from audiology, psychiatry and cognitive disorders research brought together specialists that do not usually meet, but share common patient groups and challenges. This allowed clinicians time away from their individual departments to discuss ways in which they could support each other to improve the care of patients that may unknowingly access each other’s services. For instance, implementing the use of a hearing screening pathway for patients referred for cognitive assessment to trigger a referral for audiology assessment and facilitate communication in cognitive assessments. Where possible, clinical stakeholders should include those with a range of experience from newly qualified to consultant level, to tap into both new

learning and wealth of experience. Consideration should also be taken to include geographical variance to allow for deviances in service delivery away from national guidelines. Woods et al. [92] used co-design to develop a mobile health application in the area of cardiac health, also concluded that using participatory design within a healthcare delivery setting with multiple clinicians improves patient-centered care. Using participatory design with multi-disciplinary stakeholders can facilitate a wider and unforeseen positive impact across service delivery both locally and nationally.

When focusing on designing an application to be used in a pre-clinical symptomatic population it is prudent to recruit from multiple sources outside of the standard clinical settings, such as hospitals and primary care clinics. Groups in the community such as clubs, neighbourhood associations and religious groups should be targeted as potential sources of recruitment as they are likely to include stakeholders that may have symptoms that are not severe enough to seek clinical intervention and are therefore not frequenting clinical settings such as audiology or cognitive disorder clinics.

It can also be useful to include stakeholders from a wider pool that, although may be less relevant to the prospective end users, can offer ideas for future implementation of the application. Using stakeholders that have already experienced a condition can provide data on past experiences. These stakeholders are also useful in patient and public involvement activities before data collection begins to advise on research question development, advertising materials and focus group questionnaire design.

Developing Content and Gameplay

When asking stakeholders to contribute in designing content for a new game or task that requires an element of training or behaviour change, it is important to begin the discussion by asking the stakeholders about hobbies or activities that they already enjoy participating in. Particular focus should be given to why they enjoy them and what stimulates them to regularly participate in that particular activity. For example, in cycle 2 the playing of online chess and online crosswords were introduced as an enjoyable platform for distraction, competition and

accessibility at all times of the day.

The reasons behind successful adoption and enjoyment of other applications should be understood and consequently integrated into tasks for the new game in conjunction with recommendations from the literature specifying special attention to customisation and individualisation. This was evident when discussing design for different scenarios. Stakeholders foresaw that they were more likely to regularly use the application if the scenario was individualised to an environment that they associated with enjoyment or relaxation, such as an exercise class or an art gallery. Additionally, they were also likely to use it if it was customised to a situation that they found difficult to communicate in reality and would want extra practice virtually. Examples of these included a café, airport and train station. Similarly, Jessen, Mirkovic & Ruland [37] used this approach whilst researching participatory design frameworks for a self-management application in a chronic disease population. They used common enjoyable games such as Super Mario, Crosswords and Monopoly as a vehicle to elicit further thoughts for discussion on the concept of creating their design.

3.4.6 Further development of the application

To overcome the barriers and incorporate the design needs from the findings, within the scope of the project, the application will additionally include:

- The option to deliver daily notifications to remind the user to take some time to play the application.
- Inclusion of scores and comparisons to daily or weekly high scores.
- A re-design of the visual representation to use only images as opposed to a mixture of words and images.
- Coloured boxes (green=correct; red=incorrect) that will appear around the images when selected them to notify the user of correct and incorrect selections during repeated attempts.

- A range of six realistic scenarios that are reported by people with a hearing impairment as challenging.
- Allow offline play so that users will be able to play the application during other daily activities e.g. commuting.

3.5 Conclusion

Utilising a participatory approach in conjunction with the literature base when designing a novel application ensures that the final product is useful, fun and accessible to the intended user group. Both cycles of this project have demonstrated that an application that could provide training for both auditory and cognitive performance in a way that would motivate users to regularly play it, would be welcomed as an alternative to hearing aids, a fun activity and used if it could keep the brain active and healthy. The idea of completing an active, preventative task does still not carry enough weight to drive people to use it and so would require other competitive and reward elements to overcome the barrier of having enough time to use it. The results of this study will now be used to finalise the application design and complete a randomised controlled study to evaluate the effectiveness of using the application on speech-in-noise, cognitive ability and quality of life, in addition to a usability evaluation.

3.6 Pilot Work with the Deployed Application

A short pilot was carried out following the co-design process to gather usability feedback based on the purpose of the application. Three expert application users with normal hearing were given the application to use over a 2-week period. Data logs were also collected for the play time and analysed. The three experts were recruited using an opportunity sampling method and received no incentive for completion. The experts were sent simple instructions and asked to download the application themselves via TestFlight onto their iPhones using the link to the

zipped files. Play was required across a 2-week period and a simple questionnaire was provided to obtain the usability feedback.

3.6.1 Feedback

Overall the feedback was positive with some suggestions provided for improvement.

Difficulty of downloading and playing

The first question assessed how difficult it was to download and play and the application. Two of the experts had some issues downloading the game via TestFlight due to their profile configuration. Once the developer had adjusted their access they all found it easy to download. When user testing starts, confirmation will be needed from the developer as to whether participants will need to access the application through TestFlight.

Feasibility of time spent playing

The second question stated that we are planning for this application to be used by participants for a minimum of 15 minutes per day, for a minimum of 6 times a week, across a 1 month period. Experts were then asked if they thought this was feasible, and if not, how long would be a suitable time.

Overall experts thought that this play time would be feasible and had some suggestions to keep players engaged over the 6-hour play time required over the 1-month period. This included using notifications or reminders, which is a function within the application that needs to be activated. Also being able to track progress or being able to unlock levels after a certain play time.

Suggestions to improve usability

The final question was an open question for any suggestions to improve usability. Positive feedback included that the application was easy to use and that novice application users would be able to understand what to do at each stage of the application. There was also praise for the intuitiveness of the application being able to bring the user back when giving the wrong answer and clarity by using colours to show selection of correct and incorrect answers.

Further suggestions to improve the application are listed below:

1. Clarity over certain images for:
 - Post box
 - Gas
 - Countries
2. Changing the instruction as it was originally based on the Café scenario, asking ‘Which items do you need?’ to fit the other scenarios.
3. Checking the length of the background track as where it is looping there are certain times where the sound drops out and makes it very easy to hear the instruction.

Each expert was asked to download the data logs for their play time and email them to the researcher. Each set of data logs were read through MATLAB. The results are summarised below in Table 3.3.

Expert	Correct Answers	Max Score	Min Score	Ave Signal	Ave SNR
A	65	-18	-8	-14.12	-4.12
B	104	-22	-4	-14.81	-4.81
C	75	-20	-12	-16.93	-6.93
Average	81	-20	-8	-15.29	-5.29

Table 3.3: Results for each expert’s data logs including their correct answers and SNR scores.

Analysis was also completed for performance of each expert over time see Figure 3.3.

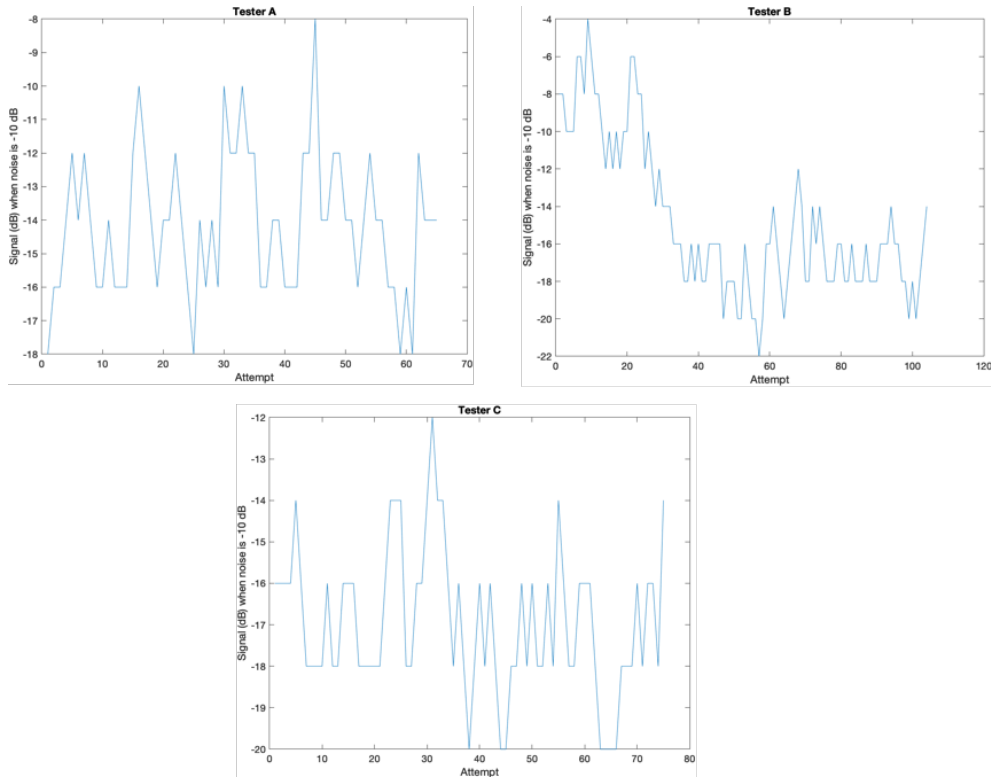


Figure 3.3: Correct responses from each expert plotted over time against the signal level.

Actions Required

Following this expert feedback the following changes were to be implemented for the evaluation of the app:

- Liaise with the developer regarding downloading the application. If it will be through TestFlight, then a short instruction sheet will need to be written. Participants will need to be aware that they are required to download this application.
- Include instructions for setting up the notification function to remind users to play every day.
- Improve the images mentioned to ensure clarity. Including adding the name of the country onto the image to negate any confusion or rely on geographical knowledge.
- Change the stimulus question to “Which pictures are mentioned in the sentence you heard?”
- Decide on a name and icon for the application.

3.6.2 Name and Logo

The pilot work suggested it would be useful for the application to have a branded name and logo for participants to identify with. It was suggested that this be clear, easily recognisable and appealing.

Two designs for the name and icon for the application were generated using the online design tool Canva [12] and presented in Figure 3.4a and Figure 3.4b.

3.4b was chosen and the tag-line was added HEaring and LIstening eXperience [HELIX] as a naming description to the application. The final and full name and logo is found in Figure 3.5.

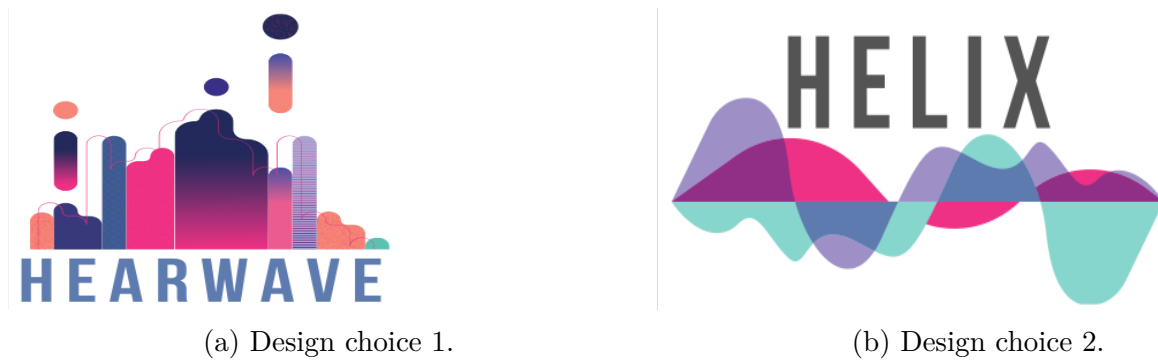


Figure 3.4: Name and logo design options



Figure 3.5: Final name and logo with description

3.7 Summary

This chapter has outlined the processes involved in utilising a co-design approach to design a deliver a functioning auditory-cognitive training application that could be evaluated by its in-

tended target population. The application was named and given a design logo that encompassed its aim and had the start of a recognised concept. The application was submitted to Apple for testing under educational and research processes, to allow a free launch of the application, with the ability to download onto individual devices free of charge.

Chapter 4

Covid-19 Disruption

4.1 COVID-19 Disruption & Plan

The global pandemic caused the data collection for the evaluation to be postponed as it was about to open for recruitment, after all clinical research activity had been suspended by the research sponsor on the 13th March 2020. All face-to-face outpatient activity was suspended in both the Audiology and Cognitive Disorders clinics at Imperial College Healthcare NHS Trust, where participants were due to be recruited from. Only clinically urgently required audiological assessment was permitted. Audiology services were initially re-instated after the 2nd lockdown, but then again withdrawn due to the 3rd lockdown, meaning the test booth and testing equipment for hearing testing and QuickSIN was unavailable.

As of March 2021, clinics began to re-open, however due to previous closures, there was a significant backlog of patients waiting to be seen under restricted clinics. Due to the backlog and staggered re-opening the availability of the test rooms, the footfall of patients accessing the department was greatly reduced, this meant that significantly fewer patients were being exposed to the recruitment posters. A change in the testing protocol was therefore required to recruit and deliver the testing virtually. Benefits of testing remotely offered opportunities for

wider recruitment across the country, reduction in requirement for physical test space and an opportunity to obtain data on new, alternative online tests. The following chapter outlines the modifications in the protocol and outcome measures that were used to deliver the randomised-controlled trial, alongside the associated challenges and decisions made in choosing alternative measures.

4.1.1 Remote Testing

The global pandemic forced audiology services to consider the potential benefits of transforming standard audiology diagnostic services by utilising remote digital solutions which had traditionally been ignored in favour of face-to-face consultations. Cancellation and closure of audiology clinics stopped routine diagnostic hearing testing altogether. This led to an increase in various online testing alternatives via web browsers and smartphone applications for simple hearing checks.

It is important to note that there are currently no online alternatives to replace the diagnostic quality and rigour of a PTA, but remote solutions were used to reduce the associated risks of no or delayed treatment, as outlined in the professional body's guidance during the pandemic [36].

Calibration

One, if not the main, issue with using remote audiological testing is the calibration of the instruments being used. In most cases the user would either download the test app or access it through a web browser on a compatible device. The user would then self-administer the test using a set of their own headphones. In this scenario there are a number of issues with the calibration of the equipment, such as types of headphones, speaker quality and volume setting that would cause any results to be treated with caution and require validation through standard audiometry, therefore negating the usefulness of using remote testing at all.

In order to overcome the issue of calibration there are some remote options that use biological

calibration. This is defined as a human check of equipment, usually performed daily by an audiologist with hearing within normal limits as part of Stage A checks carried out to detect any faults within the system, such as distortion. This is intended to regularly monitor any changes in the system between annual Stage C calibration [9]. Online offers of hearing tests began using the concept of biological calibration as a claim of validating the results.

This is true of one of the online hearing tests to actually offer a frequency specific audiogram [31]. Users are instructed to listen to a calibration audio file, then to use their own judgement of the sound level to recreate this noise by rubbing their hands together in front of their nose to achieve the same output level from the computer or device with headphones. There are many pitfalls to using this method of calibration, with multiple sources of error and bias. The use of this test would not be recommended and was not used as part of this thesis.

Screening Hearing - SHOEBOX Online

Whilst there are no solutions to replace the diagnostic standards of face-to-face audiometry, there is a potential to use remote platforms for screening and monitoring purposes. SHOEBOX online [71] is a remote platform that can be used to deliver remote hearing testing without the need for any specialised or calibrated equipment. Requirements are an internet browser, internet connectivity and a set of headphones. At the time of the thesis, it was utilised by NHS Audiology clinics as an alternative to diagnostic hearing tests for some patients, that had been suspended or heavily reduced due to the pandemic. SHOEBOX online was not deemed to be rigorous enough to be used as a diagnostic test, as the risk of it producing a false negative result when a hearing loss was present was deemed to high. Similarly, the false positive risk was also a concerning factor if the hearing results were used to fit hearing aids for the first time. It was, however, deemed suitable as a monitoring test for patients that were due a 3-year assessment and had a previous audiogram to compare the results to. If results were similar then there was assurance that the hearing had not significantly changed and fine-tuning could be completed for hearing aids.

The SHOEBOX online test comprised of a set of validated, weighted questions and a pure-tone

check at 1, 2, 4 and 6 kHz. Each frequency would then be scored from 0 - 100, whereby 0 would indicate a profound deafness or dead ear, and 100 would be deemed as perfect hearing. Again, calibration is seen as a potential measurement of uncertainty, as a generic calibration methodology is employed based on headphone and device type, both of which need to be chosen by the user at the beginning of the test. The manufacturers disclose that the test is most accurate when completed with an iPhone and over-the-ear headphones, with Android the second most accurate. They suggest that whilst wireless earphones are approximately 10 dB quieter on average, that this has been compensated for. Nevertheless, these corrections are null and void if the user does not choose the correct test set-up at the start.

Screening Cognition - ACE-III

The original pre-Covid-19 protocol included screening cognitive performance using the ACE-III assessment tool. Further detail is given in Chapter 5. Although the original protocol included delivering this screening assessment face-to-face, the developers of the screening tool did produce an online version with associated guidance on how to deliver this assessment across an online platform. It was therefore a simple adaptation to use the online version and complete the cognitive screening via an online video call with participants. Small modifications included sharing the screen so participants could see certain images and asking participants to hold up their pen and paper to the screen to complete other aspects of the screening tool.

Auditory Performance - Digit-Triplet-Test

A perhaps, more recognisable SiN platform is the DTT. This test has been validated for use in multiple languages using remote delivery vehicles such as the telephone and online platforms.

The DTT delivers a series of three random digit numbers from 0-9, within a varying SNR, using an adaptive method. There are currently a number of free online DTT that provide users with an indication of their hearing acuity and recommendation as to whether they require a full audiological assessment [87]. There are currently no freely available DTT that are delivered in

an English accent and provide a numerical score that can be analysed over repeated tests.

A new, online DTT was commissioned for use in this project using the methods utilised by a previous study with cochlear implant recipients self-administering the test using an online platform. [15].

The online DTT was developed using recordings provided by the National Institute of Health Research [NIHR] Manchester Biomedical Research unit. The digits are produced by an English female speaker with a non-regional accent for the numbers zero (pronounced 'oh') to nine, with the exclusion of the number seven. The digit seven was excluded due to being bisyllabic. The digits have been equalised to the same level both within and across digits and have the same RMS as the masker. The RMS used is -21 dB RMS. The masker is a random noise with the same RMS and spectrum as a 4-talker babble, which has been equalised to the same long-term spectrum as the digit recordings. The process for the equalisation and recording process is detailed in full in Moore et al.[55].

The parameters of the DTT used the same methodology set as that published in [15]. The first trial was presented at a SNR of 0 dB utilising a 2-down, 1-up paradigm varying adaptively. The step size was set at 8 dB and 4 dB for the first and second reversals, with 2 dB for the subsequent 8 reversals. The test used a minimum SNR of -10 dB and maximum SNR of +15 dB. The maximum number of trials is set at 60. Although the minimum and maximum levels were originally used for cochlear implant users, the levels are also suitable for people with hearing within normal limits or a mild hearing loss. On completion of the test the SNR score is generated as an average of the final 8 reversals.

The results were then stored on the server under the participant's ID number. Participants were not asked to submit any personal or identifiable data that would consequently be stored on the server. Only the researcher would retrieve the results. A publicly available version of the test is available to use and does not store any data, however does give participants the option of emailing or saving the PDF results. The publicly available test can be found at <https://d3n38zovzilbb4.cloudfront.net>

Cognitive Performance - Cognitron Test Battery

To assess and evaluate any changes over time in cognitive performance, the original protocol included the of a customised battery of cognitive tests that were due to be administered by the researcher via an iPad, with the researcher on hand to resolve any difficulties. Given the required change in protocol and removal of face-to-face activities, a small pivot in delivering the cognitive tests was deployed so that participants could access the test battery through a web page platform set-up specifically for the HELIX project. Through collaboration with Adam Hampshire and his team at Imperial College London, a test battery was created to provided assessment for a number of different memory functions. Although this meant that participants had to navigate the tests independently from the researcher, it also allowed a more diverse participant pool to be recruited as geographical restrictions for attending clinics were removed. Participants were provided with a generic link to the test battery https://helix.cognitron.co.uk/account/consent?next=/ex/task/q_ID_clearStorage and asked to input their participant ID number into the website to allow identification of results.

There were potential uncertainties of measurement with taking this approach, with mitigations that are summarised in Table 4.1. These are risks associated with the decision to move the test battery online and not general risks associated with remote testing e.g. lack of internet connectivity, drop-off or participant using another person to help them. Given the mitigations put in place, there was confidence that this would be a realistic way of collecting data on cognitive performance over time.

Quality of Life - Self-report Questionnaires

All other study questionnaires were digitalised and centralised onto one Google Form. This provided participants with a single platform to access the outcome measures in a questionnaire or directed participants to external links to complete the domain specific testing. The data could be easily accessed and analysed by the researcher and the functions within Google Forms allowed the questionnaires to be fully replicated in terms of formatting e.g. using a likert scale.

Potential Source of Error	Potential Risk to Data	Mitigations
Participant inputting incorrect participant number	Wrong participant data included	Participants reminded of their number with each reminder and sending of Cognitron link
Lack of understanding of individual task	Optimum performance not recorded	Video example played before each test to allow participants to see what they were being asked to do
Participants not completing the complete test battery without researcher there to offer encouragement	Missing data	Instructions sent in correspondence to complete each test. Data recorded for each individual test so if some tests were not completed it would not affect those that were
Participants not having access to a large enough screen to clearly see all elements of the test	Missing or incorrect data, dissatisfaction from participant that may lead to drop-off	Explanation from researcher and general encouragement given via correspondence

Table 4.1: Summary of considerations and mitigations put in place for moving the cognitive assessment battery to an online platform that was participant-led

The evaluation form was digitalised into a separate Google Form as this was only needed to be completed at the end of the study, by the training group.

Chapter 5

Stage 2: Application Evaluation

Following a successful participatory design phase and mitigations put into place following Covid-19 disruption, the next step was to test HELIX in the population it was designed for. This evaluation stage was conducted utilising a RCT with a passive do-nothing control group. To ensure a rich picture of the data was gathered, an additional qualitative data collection was completed via paired semi-structured interviews with the training group. Feedback on usability of HELIX was also collected via a validated questionnaire and through the qualitative data collection. This chapter describes the evaluation stage, the findings and how this data can inform future development of HELIX or other auditory-cognitive training applications.

This chapter has been adapted from a manuscript that is currently under review at the time of writing.

Abstract

In the dementia field, a number of applications are being developed aimed at boosting functional abilities. There is an interesting gap as to how utilising serious games can further the knowledge on the potential relationship between hearing and cognitive health in mid-life. The aim of this study was to evaluate the auditory-cognitive training application HELIX, against outcome measures for speech-in-noise, cognitive tasks, communication confidence, quality of life

and usability. A RCT was completed for 43 participants with subjective hearing loss and/or cognitive impairment, over a play period of 4-weeks and a follow-up period of another 4-weeks. Outcome measures included an new online implementation of the DTT, a battery of online cognitive tests and quality of life questionnaires. Paired semi-structured interviews and usability measures were completed to assess HELIX's impact on quality of life and usability. An improvement in the performance of the DTT, measured four and eight weeks after the baseline, was found within the training group, however this improvement was not significant between the training and control groups. No significant improvements were found in any other outcome measures. Thematic analysis suggested HELIX prompted realisation of difficulties and actions required, improved listening and positive behaviour change. Employing a participatory design approach has ensured HELIX is relevant and useful for participants that may be at risk of developing age-related hearing loss and cognitive decline. Whilst an improvement in the DTT was seen, it is not possible to conclude whether this was as a result of playing HELIX.

5.1 Background Research

Whilst throughout the ageing process developing dementia becomes a greater risk, it is not an inescapable diagnosis for all. A significant library of research has been published which has suggested a possible relationship between potentially modifiable risk factors and developing cognitive decline, which could impair functioning to an extent where a dementia diagnosis is reached. There is potential to harness these potentially modifiable risk factors to delay or slow cognitive decline through early intervention [47, 91].

Although these more recent findings concur with previous evidence [45], suggesting that hearing loss can increase the risk of developing dementia in later life by up to 5 times, the causality in this relationship is still unknown. Whilst this potential relationship between cognitive decline and hearing loss has attracted a high level of attention in recent years, more recently the literature has shifted towards interpreting these findings with caution. Healthcare professionals are being urged to ensure that the management of hearing loss is not used as a lever as a preventative

action for developing dementia and should be treated as its own long-term health condition, as highlighted by Dawes & Munro [18]. Here the authors discuss the results of the Ageing and Cognitive Health Evaluation in Elders (ACHIEVE) trial [46]. This was a highly anticipated and high quality RCT, that found a hearing intervention (hearing aids supplemented with counselling and assistive listening devices) had no impact on reducing cognitive impairment in the sample population compared to an active control in receipt of health education and chronic disease prevention. Furthermore, there is some debate in the field about the legitimacy of a secondary analysis of a sub-sample.

Moreover, a recent systematic review and meta-analysis investigating whether hearing aid use could reduce the likelihood of developing dementia was retracted due to an error in the data reporting [94]. Other studies have found that the use of hearing aids may result in lower levels of depressive symptoms and health related quality of life, but have no impact on the deceleration of cognitive function that occurs through ageing [6].

It is clear from the research and potential generalisability of findings that the focus cannot solely be placed on device-based interventions, given that hearing aid adoption in the UK is still at approximately half of the population that could benefit [5].

As highlighted by Dawes & Munro [18], *non-device based interventions* may have an effect on cognitive performance, but only if the assumption that the relationship between hearing loss and risk of cognitive decline is via a psychosocial pathway. It would seem prudent to further investigate how maximising levels of social interactions may reduce the risk of social withdrawal, which could in turn reduce depression, social isolation, better cortical stimulation and effectively reduce cognitive impairment [61, 17, 30].

One potential route to do this is through a realistic, accessible and low-barrier to entry training intervention. Home-based auditory training has shown to be time and cost effective [89]. Examples range from speech to sound sources localisation training [75]. There is a low barrier to entry, as programs can be accessed online or through downloading an application to a smart device. There is also high adoption of smart phones in age groups that could benefit from an application. In the UK in 2023, smartphone ownership was 86% for 55-64 year olds and 80% in

those 65 years plus [74]. There is also an upward trend in using smartphones for activities other than the traditional means, such as phone calls and messaging. A recent survey by The Office of Communications (the UK's government approved communication regulator) found that 38% of adults play online games on mobile devices, this is a significant increase since 2009 where the figure was only 6% [58, 74]. These factors provide an ideal opportunity to offer auditory and cognitive training on smartphones through the lens of gaming, such as a serious game [34].

A serious game is developed for a purpose other than entertainment, and can be used to train or educate the player. Multiple games have been produced to train diminishing cognition through healthy ageing. *NeuroRacer* [4] was a 3D driving game played by older adults over a 4-week period, who demonstrated improvements in working memory and sustained attention. Interestingly these two functions were not primarily targeted for training by this particular game and are so deemed off-task, as opposed to training targeted within the training known as on-task. The authors suggested a transfer of benefit occurred outside of the on-task performance. This improvement was sustained over a subsequent 6-month follow-up due to, as the authors suggest, the custom nature of the game and the fact that it was played outside of a traditional laboratory environment. Building on this work, [81] found that even the perception of a transfer of benefit is important in older adults. One key finding from their study was that if a cognitive training game was seen to be empowering, rather than supportive it could provide longer-term benefits. Participants felt that by playing a cognitive game using intellectual exercise, they could transfer this learning to sustain function through daily tasks in their real lives, such as reading, having conversations and remembering to take medication.

Within the realms of auditory and cognitive training, there are a number of studies investigating the role that SiN plays in cognition, albeit with mixed results. Research has focused on the interactions between SiN perception and cognitive performance that could signal how interventions can be designed to maximise the efficacy of future training programs.

Dryden et al.[21] conducted a systematic review assessing the association between SiN perception and cognitive ability for normal to moderate hearing-impaired subjects and whether this varied by type of outcome measure used. The review suggested cognitive performance and SiN

perception shared an association, although this did depend on the type of cognition being assessed, auditory stimuli and masker. Interestingly, the review focussed on ‘preclinical, unaided listeners’ as it was suggested that any device intervention could affect the interaction between the cognitive effort and how the degraded signals in the SiN tests were processed.

One type of cognition that has been assessed is working memory. There has been debate in the field regarding the role working memory might play in SiN perception, independent of the stimuli and masker types, but especially for those that use sentences as targets and a complex masker [65, 2]. The Ease of Language Understanding Model [ELU] [64] suggests that humans possess a stored ‘arsenal’ of phonological representations, so when there is a mismatch between this arsenal and the auditory stimulation there becomes an increase on reliance of working memory to correct this supposed mismatch. This is especially relevant in SiN perception as the mismatch may be due to background noise. It follows that those who possess a better working memory can be more adept at ironing out the mismatch, granting improved SiN [96, 33]. Again there is cause for caution to be exercised on the impact of working memory for all listeners. Füllgrabe and Rosen [28], found in normal hearing listeners under the age of 40, there was no evidence to suggest that working memory was a strong predictor of SiN ability.

Ferguson et al.[25] reported significant off-task training improvements in working memory, as well as divided attention and self-reported hearing. This was for a phoneme discrimination training task, which was sustained for a 4-week follow up period. and included reported on-task learning. Other studies have also demonstrated that untrained measures of cognition, speech perception and self-reported hearing efficacy have been improved with a degree of auditory training [3, 24, 68].

In a blinded RCT by Henshaw et al.[33], the cognitive program *Cogmed Working Memory Training* was evaluated with adult hearing aid users aged 50-75. This focused on whether training working memory processes (on-task) could better outcomes for adult hearing aid users in tasks with affinity for the training tasks and for abilities that were untrained (off-task). Whilst the experimental group demonstrated statistically significant improvements in the trained working memory task and self-reported hearing ability, there was no evidence to suggest that this

on-task learning could be generalised to untrained measures for either cognitive or SiN ability. Although the authors suggested that targeting executive functions in a combined auditory-cognitive training approach could yield the best results. Authors emphasised the importance of ensuring that the training stimuli should hold relevance to real-life listening situations where users are challenged, in order to maintain a motivation to continue; that the nature of the training should be designed by its target user groups. This suggestion draws parallels from the findings from Frost et al. [27] whereby facilitators and barriers to an auditory-cognitive training program were elicited from a participatory design process with relevant stakeholders, including service users, clinicians and researchers. From an iterative design approach 6 main themes were identified when designing an auditory-cognitive training application for users in mid-life with self-reported concerns about their hearing and/or their memory. These were (1) congruence with hobbies, (2) life gets in the way, (3) motivational challenge (4) accessibility (5) addictive competition (6) realism.

The themes demonstrated a mixture of facilitators and barriers. For instance, participants felt that the game needed to be an extension of an enjoyable hobby to garner and maintain interest. Stakeholders preferred a design aesthetic that mirrored real life, such as scenarios they would often frequent, as opposed to more gamified fantasy settings. Ensuring the game was accessible in terms of it's appearance and challenging by using multiple scenarios were also facilitators. Sharing scores to add in a competitive challenge among peers and family was deemed important for some to help overcome a potential barrier of life's other chores and responsibilities getting in the way of finding time to play.

There is scope to further investigate how working memory may interact with SSiN performance and an argument that embedding this training within a serious game, instead of a traditional training program could impact on how users can translate their learning within the game to their daily lives to provide easy-access benefits to on and off task-learning.

HELIX has therefore been developed as a serious game, to reap the benefits from transposing a traditional computer-based training program into a game-based play format. Therefore providing an auditory-cognitive training application that targets parts of executive functions via

working memory aimed at those on the periphery of age acquired hearing loss and/or cognitive impairment. By primarily targeting this group of the population i.e. those that are not using hearing interventions such as hearing aids, HELIX has the potential to provide a non-device based intervention earlier in the ageing process that can be viewed as empowering rather than supportive. Using realistic scenarios that are relevant to daily listening situations, also provides users with the opportunity to build confidence in executing daily tasks in these simulated scenarios. In this study HELIX was evaluated.

5.1.1 Aims and Objectives

The principal research question was how can prolonged training through a serious game affect speech perception in noise and cognitive performance in a mid-life population at risk of age-related hearing loss and mild cognitive impairment. The aim was to test the beta-version of the HELIX application in a sample population.

In order to achieve this aim the primary objective was to evaluate the use of HELIX on SiN performance, with additional objectives:

- To evaluate the use of HELIX on a battery of cognitive tests
- To evaluate the use of HELIX on communication confidence
- To measure the impact of HELIX on quality of life through self-report
- To measure the usability of HELIX through self-report

The hypotheses are:

1. Continuous play across the training period will result in improved speech-in-noise recognition scores measured by a quick speech-in-noise test.
2. Continuous play across the training period will improve cognitive performance as measured by a cognitive test battery.

3. Continuous play across the training period will result in improved communication confidence and quality of life via self-report questionnaires.
4. Participants will report a positive transfer of benefits through thematic qualitative analysis.

5.2 Materials and Methods

This study was originally reported in the journal paper submission in accordance with the CONSORT statement [70] and the COREQ checklist [84]. The study was approved by the London - Bromley Research Ethics Committee (Reference number 19/LO/1662).

5.2.1 Participants

Participants were recruited from a variety of sources including NHS Audiology and Cognitive disorder clinics, Join Dementia Research which is funded by the Department of Health and Social Care and delivered in partnership by the NIHR, Alzheimer Scotland, Alzheimer's Research UK and the Alzheimer's Society, and social media across England. All participants gave written informed consent and were provided with a £25 Amazon voucher on completion of the study.

Participants were required to meet 5 inclusion criteria: (i) 40-75 years old (ii) report mild subjective concerns regarding their hearing and/or their memory, (iii) not using hearing amplification (iv) not have a formal medical dementia diagnosis (v) to be able to use an iPad or iPhone without need for assistance. To supplement the self-declaration of criteria (ii), screening tests were carried out to confirm participants did not have a suspected moderate-severe hearing or cognitive impairment. Data collection was completed between May and November in 2022. Due to the recovery of health services following the Covid-19 lockdowns it was not possible to complete face to face hearing tests (PTA), the entirety of this study was therefore digitalised to reduce footfall in hospitals and reduce risk for participants. SHOEBOS online [83] was used as

a hearing screening measure for participants to complete via a personalised link. Participants were required to score between 70-100 indicating normal hearing or between 30-70 indicating a mild to moderate hearing loss. A score of 30 or less would indicate a significant loss and participants would therefore be excluded and referred on for management. This hearing screen could be completed on any device with any headphones. This online screen was chosen as it was utilised by NHS Audiology services during the pandemic to screen and reassess hearing. The ACE-III Remote Administration - UK Version A [35] was used to screen for cognitive impairment and was completed via a video call between the lead researcher and participants, using the participants' preferred platform. Participants were required to score at least 82/100, indicating normal or mildly-impaired cognition, as a score of less than 82 would be indicative of more severe cognitive impairment requiring management.

A sample size calculation was computed for a 2-sided significance of 0.05, a power of 80% and effect size of 0.89. This calculation required 21 participants per group, 42 in total.

56 participants met inclusion criteria, of those 48 completed and passed both screening measures. A further 5 participants dropped out across the course of the study, resulting in 43 participants who completed (28 females:15 males; aged 40-74; M=60.16 years old, SD=8.10)(see Figure 5.1).

Participants were allocated to either the Training Group (TG) or a passive Control Group (CG) using the minimisation method, as used in a similar study design [24]. Similar grouping variables were used in this current study, which were better ear hearing scores on SHOEBOX Online (better ear between 70-100; poorer ear between 30-69) and gender. Age was also used as a grouping variable, the protected age grouping variable was younger (40-57):older (58-75). A summary can be found in Table 5.1.

5.2.2 Study Design

Participants completed a set of baseline outcome measures to assess a range of performance and self-report. Following randomisation, the TG were asked to download the application HELIX

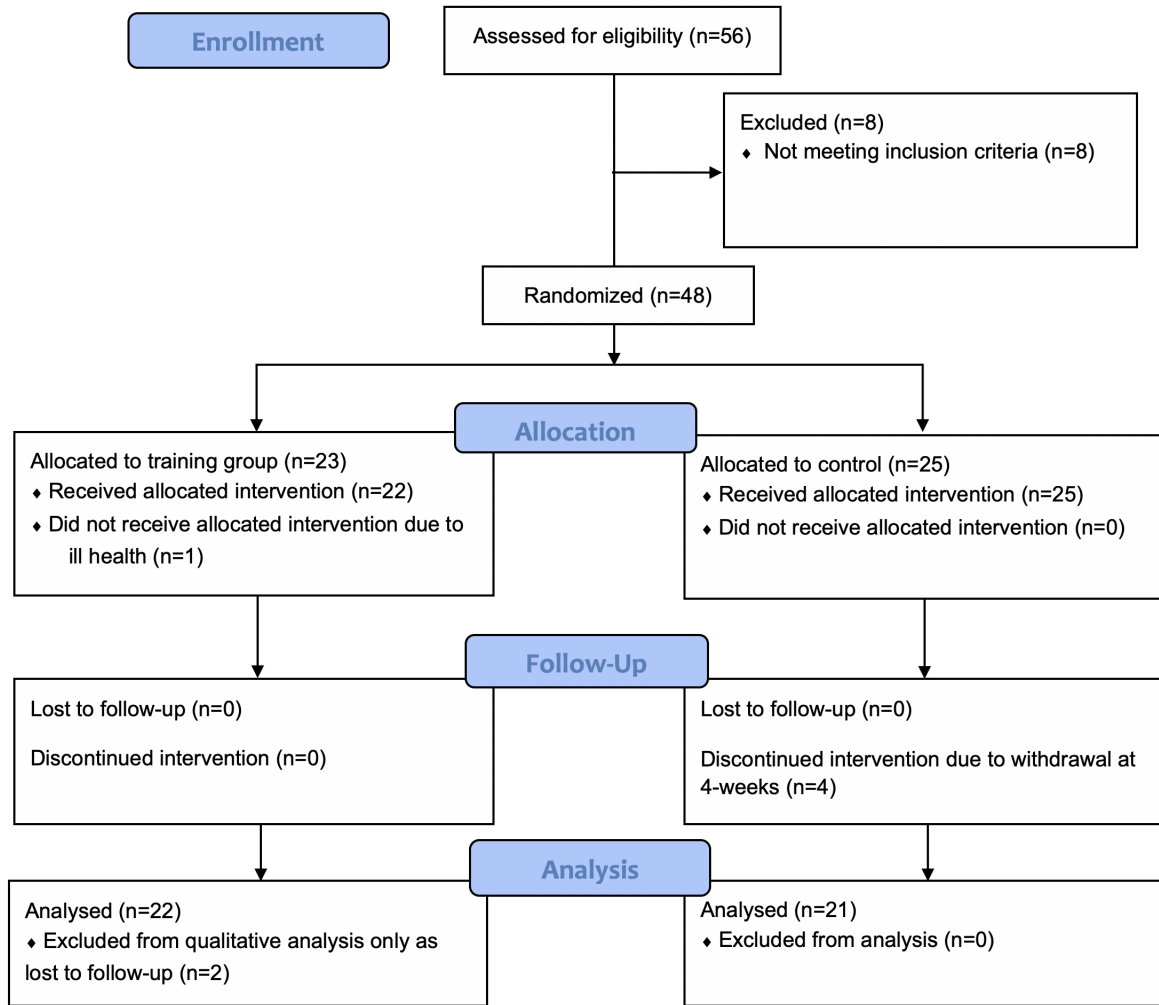


Figure 5.1: CONSORT flow diagram detailing how participants were enrolled, allocated, followed-up and analysed. This includes any participants that were excluded or did not continue for the whole duration of the trial.

onto their own iPad or iPhone using TestFlight. Written instructions on how to download the test application were provided with easy-to-follow steps, screenshots and invitation link. Once downloaded participants were asked to set the URL to access the content and were given the option to enable notifications to remind them to play daily.

If participants did not have access to an iOS device, a loan device was provided for the duration of the study with the application installed and notifications enabled.

A second set of written instructions were provided explaining how the application should be used, this was for a minimum of 10 minutes per day, for 6 days per week for 4 weeks. This was the same method used for the weekly play time in a similar study [24], whereby participants

Grouping Variable	TG (n=22)	CG (n=21)	Between Group Comparison	
			Fishers/t	p
Gender (M)	8	7		
Gender (F)	14	14	n/a	1.00
Mean Age (SD)	59.1 (6.97)	61.24 (9.19)	-0.85	0.40
Mean Better Ear (/100) (SD)	71.36 (12.88)	76.76 (14.52)	-1.29	0.20
Mean Poorer Ear (/100) (SD)	66.50 (13.70)	71.29 (19.32)	-0.94	0.35
Mean ACE-III (/100) (SD)	93.95 (3.29)	93.33 (3.14)	0.63	0.52

Table 5.1: Comparison of grouping variables between TG and CG groups. Whilst overall hearing score was not used as a grouping variable, 22 participants in the training group were categorised as good hearing and 11 out of the 21 in the control group were categorised as good hearing. This was indicated by a score greater than 70/100 on SHOEBOX Online.

recorded a high compliance. There were no dropouts during the training period, it was therefore assumed that using a similar design in a similar participant pool would yield adequate levels of participation and usable data. After completing their 4 weeks of play, the TG were required to download and send their data log files of the game play to the researcher. A user experience questionnaire and paired semi-structured interviews were also completed for the TG to conduct an evaluation of the application and obtain qualitative data to aid in answering the secondary objectives. Outcome measures were repeated by all participants after 4 weeks - to assess any initial changes, and after 8 weeks to assess any longer-term changes without application play. An overview of the study design can be found in Figure 5.2.

5.2.3 Application Design

Procedure

HELIX was designed to provide auditory-cognitive training through two main tasks. In each scenario users were first presented with an auditory task. This required them to listen to an instruction (stimulus) and correctly identify it from a multiple choice of 4 similarly worded text options used as distractors. The auditory instruction would be presented within a masker produced to replicate the environment in each scenario. The masker for each level was designed to specifically mirror typical content for that scenario to maintain auditory realism, rather than

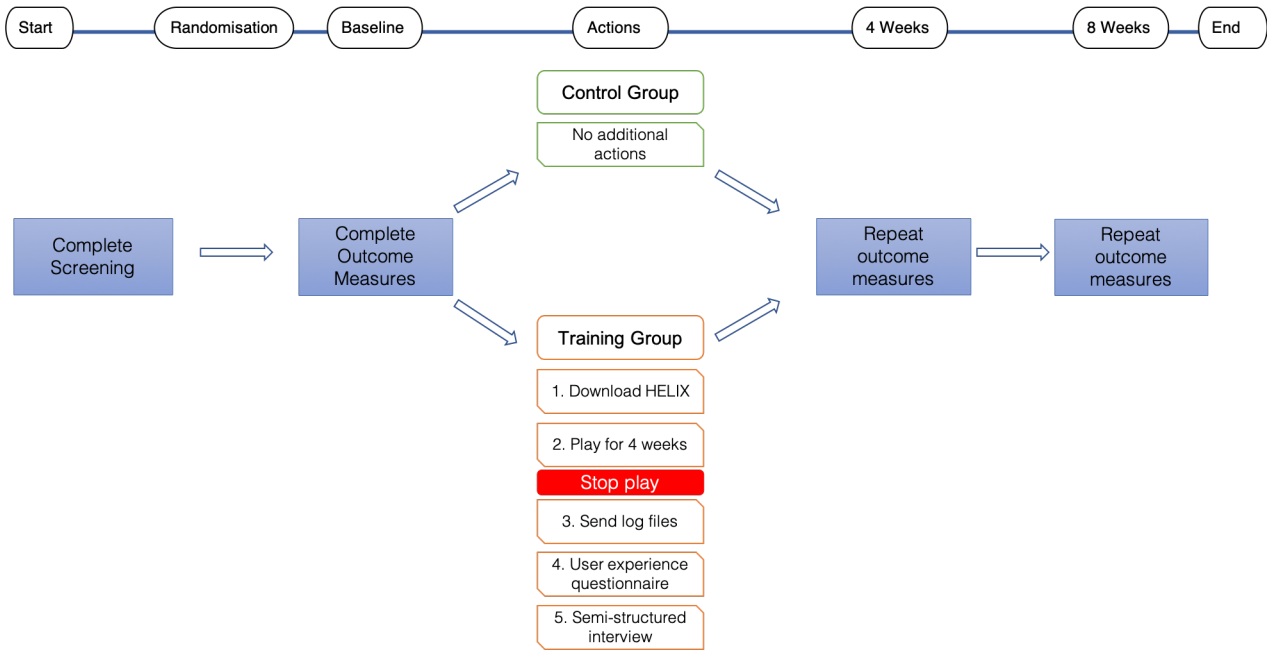


Figure 5.2: Overview of study design showing data collection and action points for all participants.

using a multi-talker babble for each scenario. For each scenario 2-3 main auditory maskers were identified. Free to use audio files for each masker were downloaded from open access sound effects websites. Each masker was then uploaded into the 3D Tune-In Toolkit [14] for the spatialisation, which was performed in the binaural domain, therefore specifically for headphones playback. 30-second virtual soundscapes for each specific scenario were created. The target stimulus was spatialised as well using the same method. A summary of the maskers is included in Table 5.2. An incorrect choice would trigger the replaying of the stimulus at a +2 dB more favourable SNR, with the same multiple choice options until the correct answer was chosen, although the order of the text options varied each time. This ensured the stimulus was audible enough to understand the instruction before moving to the cognitive task.

This second task was a recall task, targeting working and immediate memory. Participants were required to select images that represented the key words in the auditory instruction from the previous task. If all keywords were chosen correctly, the user would move onto the next level at a less favourable SNR. If incorrect, the user would receive feedback on how many images were correct, incorrect and how many more/less were needed. The user would be given 3 attempts before being asked to move to the next level at the same SNR. See Figure 5.3 for screenshots

demonstrating the tasks and interface.

Scenarios

Users had 6 scenarios available, with 10 levels per scenario equalling a total of 60 levels. Participants were asked to play each scenario at least once across the 4-week play period, following this they could choose which scenarios to play and how many levels to complete as long as it satisfied the 10 minute per day criteria. The scenarios were chosen based on the participatory design process [27] and literature base, as they represented environments that the users would regularly frequent in their daily lives, that would provide a challenging auditory soundscape, yet also require cognitive resources; thus providing a situation that would require speech recognition, understanding and cognitive recall. The scenarios chosen were as follows:

- Train Station
- Post Office
- Café
- Supermarket
- GP Surgery
- Theatre

In each of the scenarios, the 10 levels were organised to increase in difficulty as the scenario progressed. Levels 1-3 (easy -1), 4-6 (medium-2) and 7-10 (hard-3).

For example, in the train station scenario, the easy tasks consisted of three key words or phrases:

(Easy) The **13:15** to **Bristol Parkway** will depart from **platform 14**.

The distractors for the key words were simple, such as Bristol Temple Meads, Bristol, 14:15 and platform 15.

For medium tasks, the difficulty increased by introducing a fourth keyword or phrase, therefore adding to the cognitive load of the task.

(Medium) We're sorry to announce that the **16:47** to **Birmingham Moor Street** has been **delayed** by **17 minutes**.

For hard tasks, the number of key words or phrases remained at 4, but become more complex in their instruction with multiple numbers or timestamps that could be easily misheard and mis-remembered, relying on greater cognitive resources to achieve the correct answer.

(Hard) Your seat reservation is for **Coach C**, seat **23**, **B** on the train to **Leeds**.

Users would not be able to proceed to the cognitive task until the auditory task was correctly completed.

The coding of the application was completed using a JavaScript Object Notation file for each scenario using the software Sublime Text v3.2.2. Each scenario required it's own JSON file in conjunction with the scenario's corresponding audio and images. An example of level 1 in the Cafe scenario is demonstrated below:

```
"title" : "Cafe",
"maximumRetryAttempts" : 3,
"initialSignalDBFS" : -20.0,
"noiseDBFS": -10.0,
"signalDBIncrementAmount" : 2.0,
"noiseAudio" : ["audio/cafebackground.wav",
"audio/cafebackground.wav"],
"challenges": [

"audio": "audio/coffeemilk.mp3",
"incorrectConfirmationOptions" : [
```

```

"Please can I pay the bill",
"Please can I have a cup of tea",
"Please can I have a hot chocolate"

],
"correctConfirmationOption" : "Please can I have a coffee with milk",
"level" : 1,
"correctRecipeLabels" : [
],
"incorrectRecipeLabels" : [

],
"correctRecipeImages" : [
"images/milk.png",
"images/coffee.png",

],
"incorrectRecipeImages" : [
"images/tea.png",
"images/hotchocolate.jpg",
"images/coldwater.png",
"images/creditcard.png",
"images/loosechange.png",
"images/sugar.png"
]

```

All audio files were recorded by the researcher, a female speaker, using a Blue Snowball USB microphone and Audacity v2.3.2. All recordings were completed in the same session to ensure consistency. Signal levels were modified where needed in order to ensure that all stimuli were reproduced at the same RMS level, and calibrated with the background maskers.

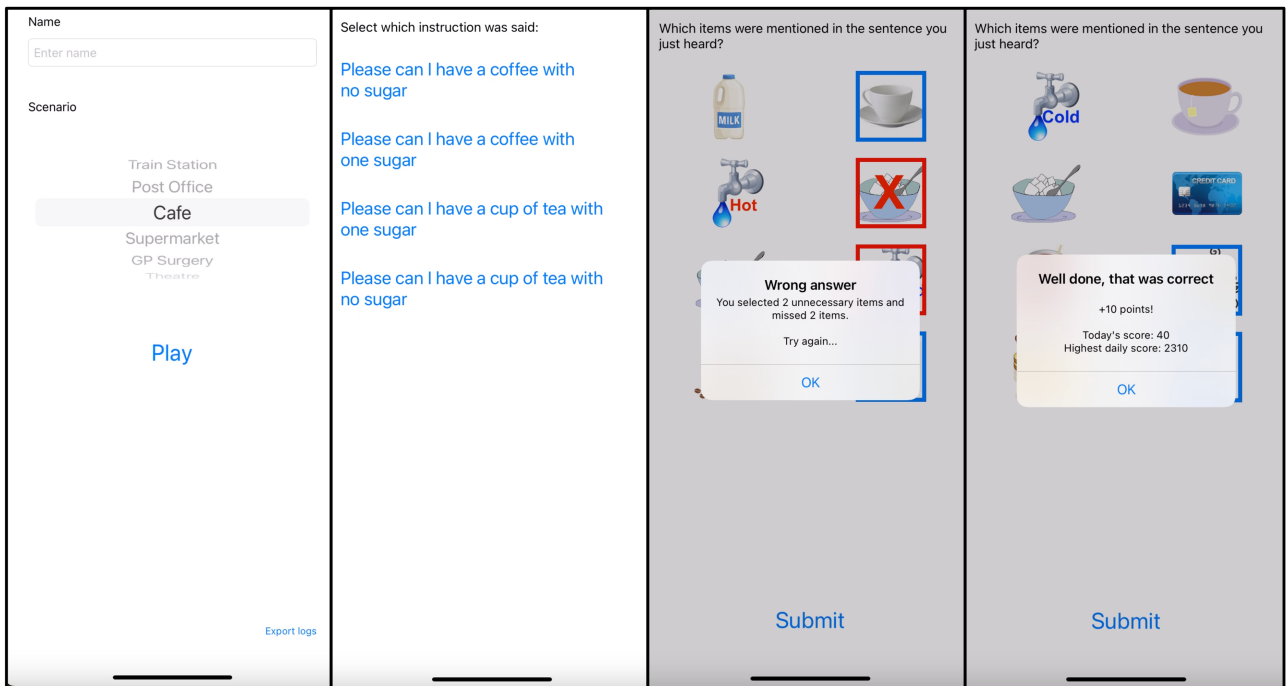


Figure 5.3: Examples of screenshots including the Home-screen with scenario choice, multiple choice for auditory task, example of feedback with encouragement to retry and positive endorsement with scoring on correct answer triggering progress to the next level.

Scenario	Masker 1	Masker 2	Masker 3
GP	Telephone ringing	Persistent Cough	Conversation
Supermarket	Trolleys	Musac	Barcode Scanning
Post Office	Conversation	Money counting	N/A
Train Station	Tannoy announcement	Trains departing	Outside conversation
Theatre	Conversation	Children speaking	N/A
Café	Conversation	Plates and Cutlery	Coffee machine

Table 5.2: Description of the key auditory maskers used for each scenario

5.2.4 Outcome Measures

Measures were chosen based on their reliability, validity and ability to be delivered online or remotely without impeding their effectiveness.

Digit Triplet Test

Speech recognition in noise was assessed using a newly-developed version of the DTT, based on the parameters used in Cullington & Aidi[15]. This version of the DTT was designed to give a SNR output score in dB, as opposed to other online implementations which output only

qualitative data about the subject’s performances, allowing this to be used as a quantitative monitoring tool. The DTT was implemented into the online platform using recordings made with support from the NIHR Manchester Biomedical Research Centre [55]. A secondary version of the DTT which does not store results and is available for public use can be accessed via www.axdesign.co.uk/tools-and-devices/digit-triplet-test.

Cognitive Tests

Cognitive performance was measured online via a customised battery of tests from a cognitive assessment platform (Cognitron), to remotely assess cognitive performance. A platform was set up specifically for this study, with particular tests chosen to measure and monitor performance in domains that HELIX targeted and may produce a transfer of benefit. Table 5.3 details the name of the test, assessment type and short description.

Self-Report

For this study the 12-item Communication Confidence Profile CCP was chosen to assess participants’ confidence in effective communication via a range of communication skills [77]. A second self-report measure was used to assess quality of life. The WHO Quality Of Life Age (WHOQOL-AGE) questionnaire, was chosen as a short 13-item questionnaire designed as a specific tool to assess quality of life in an ageing population [11]. Links to both the DTT and Cognitron test battery platforms were accessible alongside the self-report questionnaires through a Google Form, sent to each participant at each time-point.

In addition, 8 paired 60-minute semi-structured interviews [19] were conducted with the training group via Zoom by the lead author(EF, female), who had previous experience in conducting interviews. Only audio was recorded. The purpose was to explore the impact of using HELIX on quality of life and to elicit more detailed feedback on the usability of HELIX. Due to technical issues joining the Zoom call or scheduling conflicts, 3 participants completed their interviews alone. 2 participants did not complete interviews. Paired semi-structured interviews were used

Test Type	Assessment Type	Description of Test
Prospective memory-world list	Immediate memory	List of words shown, users then asked to select yes/no to whether words were on the original list with distractors added.
Target detection	Attention	Users pick out a target shape from a panel of other shapes as quickly as possible with new shapes appearing throughout.
Selective attention	Attention	Users select the direction of a smaller arrow (L or R) within a bigger arrow, ignoring the direction of the bigger arrow.
2D Manipulations	Planning, manipulation, and information processing	Users look at the top coloured pattern of squares and identify which of the four suggested patterns is the same pattern rotated.
Blocks	Blocks	Users asked to remove shapes from the first square to match the silhouette in the second square. Unsupported blocks fall to fill the gaps.
Tower of London	Planning and reasoning	Users are shown two sets of pegs and must work out the fewest number of moves needed to make the top peg set the same as the bottom peg set.
Spatial span	Working memory	Users shown a series of squares highlighted one at a time in a grid, after a short delay users must click the squares in the order they first appeared.
Choice reaction time	Attention and information processing	An arrow points left or right, users must click/touch the side of the screen the arrow points to as quickly as possible.
Verbal analogies	Verbal reasoning	Users must select true or false on whether two pairs of words relate to each other in the same way.
Sustained attention to response	Attention	Numbers appear from 1 to 10 in order. Users must click/touch every number except the number 3 until the test ends.

Table 5.3: This shows the different test types used in the Cognitive assessment battery, including which particular function the test was assessing. A description of what the users were asked to do to complete each test is also included. Users could not progress to the next test until the previous test was completed. A percentage completion bar was displayed at the bottom of the screen at all times.

with a topic guide, which is included in the appendices. Field notes were made by the lead author during the interviews. Audio recordings were transcribed in full, stored and coded in Nvivo (Version 14). Coding was completed by the lead researcher and a contributing author to the paper, with experience in thematic analysis.

Finally the training group completed the User Experience Questionnaire (UEQ). This was primarily used to assess usability and experience to provide data that may be used to improve the application in the future. Secondly it was used to identify any possible trends that may account for the data obtained in any of the other outcome measures, for example a lack of stimulation, efficiency or originality.

The tool is a standardised measure of a user's experience of a digital interface [44] designed to assess usability and engagement across six user experience dimensions via 26 items rated on a 7-point Likert scale. These were attractiveness (aesthetics), perspicuity (ease of learning), efficiency (was it productive), dependability (was it reliable), stimulation (was it engaging), novelty (was it innovative). Participants were asked to rate each of the 26 items. Data were collected for 17 training group participants.

5.3 Results

Data analysis was carried out using MATLAB R2023a. Descriptive statistics for all outcome measures can be found in Table 5.4. A Mixed Analysis of Variance (ANOVA) was completed to examine the group:timepoint interaction. The group factor was between subjects in the TG and CG, and timepoint was for each of the three data collection points: baseline, 4-weeks and 8-weeks. A third factor of 'subject' was included as a random factor to account for the repeated measure within each participant. All reported statistics can be found in Table 5.5.

Outcome Measure	Group	Baseline			4-weeks			8-weeks		
		Mean	Median	STD	Mean	Median	STD	Mean	Median	STD
DTT	Training	-4.80	-5.13	1.98	-6.05	-6.00	1.30	-6.22	-6.38	1.23
	Control	-5.41	-5.38	1.25	-5.76	-6.25	1.78	-5.42	-6.00	3.25
Communication Confidence Profile	Training	41.41	44	8.03	39.19	39	7.90	39.23	39	7.53
	Control	43.52	44	7.38	42.62	44	6.57	42.48	43	7.33
Quality of Life	Training	44.27	44.5	7.72	44.52	45	7.15	45.09	46	6.93
	Control	48.57	50	7.22	46.05	48	8.71	46.62	48	7.70
Prospective Memory Word	Training	22.5	22	1.19	22	23	1.13	22	22	1.38
	Control	22	22	1.41	22.68	23	1.45	22.15	22	1.71
Target Detection	Training	56.6	60	12.38	45.6	61.5	11.72	59.9	62	9.98
	Control	50.75	51.5	10.67	53.16	60	14.09	51.86	53	14.47
Selective Attention	Training	687.52	674.5	114.6	686.85	675	118.97	698.65	690.5	113.42
	Control	774.03	758.5	164.07	695.63	679	99.82	714.93	740	114.47
2D Manipulations	Training	24.8	25	7.42	25.8	27.5	5.44	28.35	28.5	7.49
	Control	24.85	27	5.49	27.37	27	7.51	29.48	28	7.85
Blocks	Training	10.5	10	2.76	10.85	11	2.21	11.25	11.5	2.53
	Control	10.55	11.5	2.67	10.95	13	3.14	10.10	11	3.05
Tower of London	Training	6.3	7	2.3	6.7	7	2.13	7.21	8	2.35
	Control	6.25	7.5	2.88	6.21	7	2.68	6.14	6	2.54
Spatial Span	Training	5.26	6	1.33	5.35	5.5	0.81	5.53	6	1.02
	Control	5.65	6	1.18	5.89	6	1.15	5.1	5	1.09
Choice Reaction Time	Training	606.53	597.02	99.86	608.70	601.17	82.26	590.73	609.26	113.98
	Control	623.89	654.87	168.9	622.72	629.35	174.54	602.25	618.93	164.57
Verbal Analogies	Training	18.68	19	12.28	25.05	26	7.8	30.68	29	10.91
	Control	19.19	18	13.44	21.8	22.5	14.17	25.18	23	13.70

Table 5.4: Summary of average scores for all outcome measures for Training and Control Groups at Baseline, 4-weeks, and 8-weeks.

Outcome	F	p	η_p^2
DTT	(2, 3.07) = 1.16	0.32	0.01
Communication Confidence Profile	(2, 5.124) = 0.56	0.57	<0.01
Quality of Life	(2, 25.78) = 2.48	0.09	<0.01
Prospective Word Memory	(2, 1.72) = 1.79	0.17	0.01
Target Detection	(2, 33.15) = 0.3	0.74	<0.01
Selective Attention	(2, 11909.4) = 2.25	0.11	0.01
2D Manipulations	(2, 2.60) = 0.14	0.87	<0.01
Blocks	(2, 3.85) = 1.03	0.36	<0.01
Tower of London	(2, 1.93) = 1.04	0.36	<0.01
Spatial Span	(2, 2.40) = 4.51	0.01	0.03
Choice Reaction Time	(2, 128.80) = 0.04	0.96	<0.01
Verbal Analogies	(2, 66.93) = 2.03	0.14	<0.01

Table 5.5: Statistical reporting for Mixed ANOVA for the group:timepoint interaction for each outcome measure. After applying the Bonferroni correction due to multiple comparisons, the corrected alpha value was 0.004.

5.3.1 DTT

Additional statistics were completed on the primary outcome measure only to look for any significant effects. A further repeated measures ANOVA within groups was completed for the TG to assess the impact of using HELIX across the three data collection points - Baseline, 4-weeks (after 4-weeks of regular use), 8 weeks (following a 4-week period of not using the app). A significant effect of time was found ($F(2,40)=6.11$, $p \leq 0.01$, $\eta_p^2 = 0.23$ in the TG, but was not present in the CG. Post-hoc repeated t-tests were completed which showed a significant difference between baseline and 4-weeks, $p \leq 0.05$ and between baseline and 8-weeks, $p \leq 0.01$. There was no significant difference found between 4-weeks and 8-weeks.

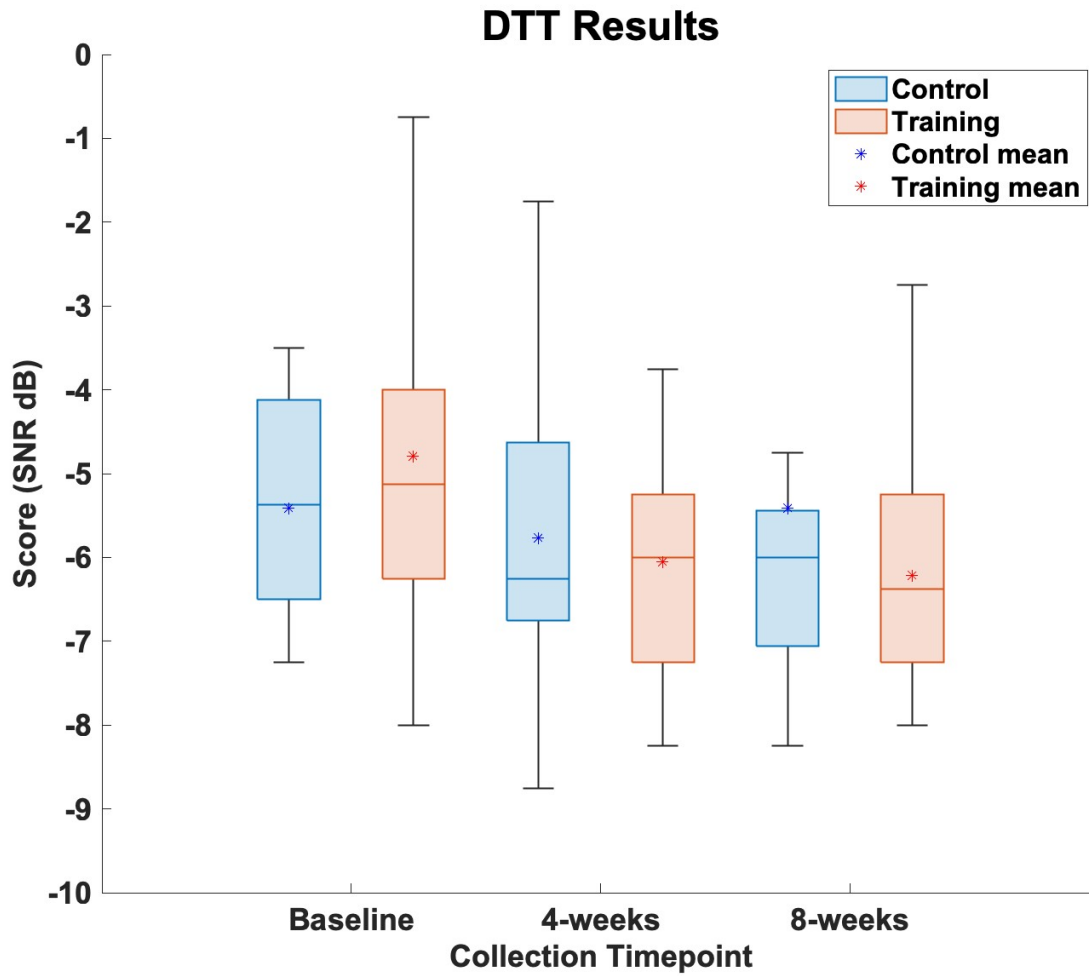


Figure 5.4: Paired boxplots demonstrating total DTT scores for both groups at each collection time point.

5.3.2 Cognitive Tests

Statistical analysis showed there were no significant improvements after using HELIX in the cognitive tests. An initial potential change was noted in the Spatial Span test, however this was not deemed significant after applying the Bonferroni correction. This provided a corrected alpha value of 0.004.

5.3.3 Self-Report Measures

There were no significant differences found in either the CCP or the Quality of Life measures between groups.

5.3.4 User Experience

The UEQ was analysed using the UEQ Data Analysis tool. The questionnaire measured the use of the application across 6 domains: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation and Novelty by asking users to rate between two categories e.g. annoying or enjoyable. The analysis tool rates the scale from -3 (horribly bad) to +3 (extremely good). Overall the scores can be interpreted as follows: less than -0.8 as negative -0.8 to +0.8 as neutral and greater than 0.8 as positive. Positive scores were received for attractiveness, perspicuity, efficiency and dependability, whereas stimulation and novelty received neutral scores. The highest scores reflect the application's perspicuity, with more positive evaluations towards understandable, easy to learn, easy and clear. The lowest scores were recorded for stimulation, with more neutral scores given for boring/exciting and not interesting/interesting. There was a more positive score received in this scale however for the pairing inferior/valuable. Mean values per item are listed in Table 5.6.

Rating	Mean	Variance	Std. Dev.	Left	Right	Scale
Neutral	-0.5	2.0	1.4	annoying	enjoyable	Attractiveness
Neutral	0.6	2.5	1.6	attractive	unattractive	Attractiveness
Neutral	0.8	2.9	1.7	unlikable	pleasing	Attractiveness
Positive	1.0	2.1	1.5	unpleasant	pleasant	Attractiveness
Positive	1.4	1.5	1.2	good	bad	Attractiveness
Positive	1.6	1.4	1.2	friendly	unfriendly	Attractiveness
Neutral	0.6	2.1	1.5	obstructive	supportive	Dependability
Positive	1.0	2.9	1.7	secure	not secure	Dependability
Positive	1.0	1.9	1.4	meets expectations	does not meet expectations	Dependability
Positive	1.1	1.8	1.3	unpredictable	predictable	Dependability
Neutral	0.5	1.9	1.4	fast	slow	Efficiency
Positive	1.3	1.8	1.4	inefficient	efficient	Efficiency
Positive	1.4	1.9	1.4	impractical	practical	Efficiency
Positive	1.4	1.9	1.4	organized	cluttered	Efficiency
Neutral	0.8	3.4	1.9	creative	dull	Novelty
Neutral	0.8	1.8	1.3	inventive	conventional	Novelty
Neutral	0.8	1.2	1.1	usual	leading edge	Novelty
Positive	0.8	1.7	1.3	conservative	innovative	Novelty
Positive	1.1	2.0	1.4	clear	confusing	Perspicuity
Positive	1.4	3.4	1.8	not understandable	understandable	Perspicuity
Positive	1.5	1.8	1.3	complicated	easy	Perspicuity
Positive	1.9	2.1	1.5	easy to learn	difficult to learn	Perspicuity
Neutral	0.1	3.4	1.8	boring	exciting	Stimulation
Neutral	0.4	3.2	1.8	not interesting	interesting	Stimulation
Positive	1.1	2.6	1.6	motivating	demotivating	Stimulation
Positive	1.4	1.6	1.3	valuable	inferior	Stimulation

Table 5.6: Results from the UEQ tool - Column 1 - Rating refers to the categorisation each item was given, with columns 2, 3 and 4 referencing the score, whereby -3 (horribly bad) to +3 (extremely good). The Left and Right columns include the descriptors for each question, which were either positive or negative ends of the spectrum.

5.3.5 Data Logs

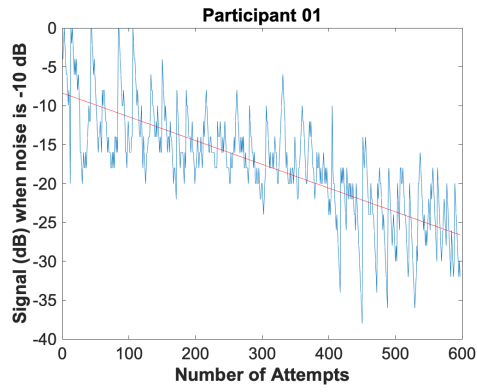
In addition to data logs, a t-test was carried out to analyse performance at the start and the end of the play period. The result from the start ($M=-12.10$, $SD=4.07$) and end ($M=-15.62$, $SD=5.68$) demonstrated an improvement in performance $t(40)= 2.31$, $p \leq 0.05$. A demonstration of change from start to finish for all participants is shown in Figure 5.5 and a selection of the logs are included in Figure 5.6.



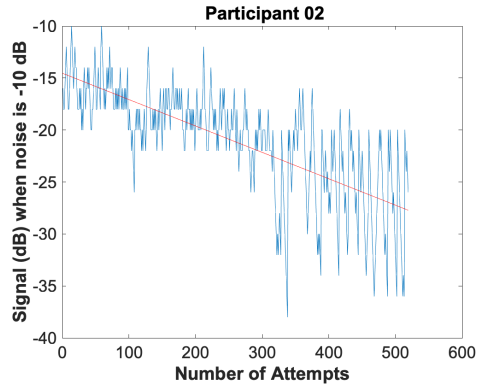
Figure 5.5: Boxplots demonstrating the SNR at the beginning of the 4 week training period and the end, * indicates the mean values, + indicates outliers.

5.3.6 Qualitative Analysis

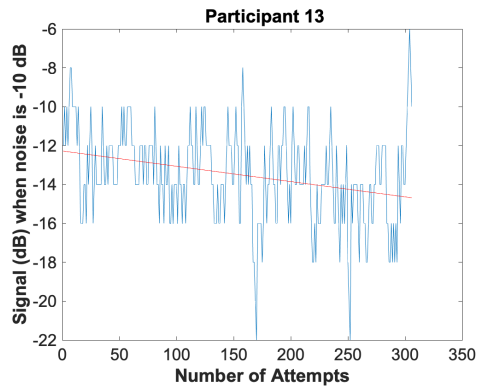
A thematic analysis approach [7] was used to establish themes based on the effectiveness of HELIX on quality of life and its general usability.



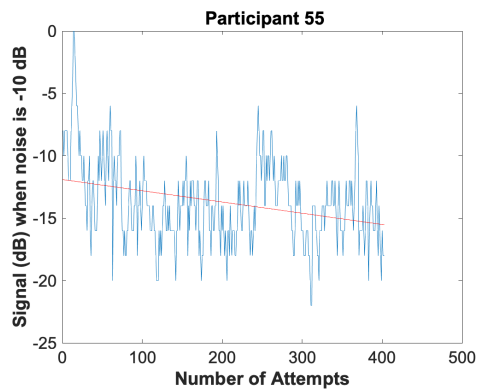
(a) Data logs for participant 01



(b) Data logs for participant 02



(c) Data logs for participant 13



(d) Data logs for participant 55

Figure 5.6: Plots displaying the signal amplitude compared to the noise signal of -10 dB for all attempts during the 4 week period for a selection of participants. A line of best fit has been added to highlight change over the play period.

3 themes emerged around quality of life, which were (1) Immersive scenarios prompted realisation of difficulties and actions required (2) Gameplay fostered improved listening and recall self-efficacy and (3) Positive behaviour change. 3 themes on usability which were (4) Repetition obstructed engagement (5) Easy to incorporate into daily life (6) Improved scoring system required to be motivational.

Immersive scenarios prompted realisation of difficulties and actions required

Participants reported that not only did HELIX highlight their existing issues with their hearing and memory, but it also made them realise the difficulties they encountered in their daily lives. There was a consensus that because the immersive scenarios used were realistic and relatable, this prompted them to reflect more on how they were performing in their real lives, such as at work or with their families in terms of their hearing more so than memory.

You can see with your own eyes how much you struggle so it's not just a subjective thing that is happening when you are in a Café or you are out and about with your friends (P3)

One of the things I started doing in the app was guessing, I wasn't actually hearing it properly and then I realised I was doing that a lot in spoken conversation. (P9).

Not only did it cause self-reflection over their challenges with their hearing and memory, it also prompted action.

I should be getting an Audiology test and I would accept that I probably need hearing aids of some description. (P11)

I think it is definitely something, on the way to get some help (P56)

I'm going to go and get a hearing test. (P40)

Gameplay fostered improved listening and recall self-efficacy

The repetition within HELIX provided players with increased confidence as they found across the 4-week play period that they were able to remember the keywords in the auditory stimuli. This familiarity with the scenarios and relationships between the stimuli and response options allowed players to leverage the memory of past experiences, contextual cues and deductive reasoning to then formulate informed guesses or assumptions, especially when the comprehension of the key words became harder. Players were then able to complete more content within their 10 minute play time which gave a sense of improvement and achievement.

Yes, it changed my confidence, as time went on I found I nearly completed three levels, because I became quicker as the time went on because I could remember the questions. (P1)

Specifically, participants commented that their listening skills improved from playing HELIX, as it highlighted how important concentration was in listening to and recalling information. Participants found when they actively concentrated they yielded better results in the game, again boosting confidence their own abilities to replicate this in the real world, especially in unfamiliar environments.

I'd probably feel a little bit more confident maybe, because they would probably be realistic in what you would expect to hear at a post office or a train station, being pre-warned is a little bit more information which makes me feel a bit more confident. (P8)

You're pre-empting things, you're listening better, you actually are sort of really more focused on it because you are breaking down that noise barrier and actually listening to it. (P9)

Positive behaviour change

Despite the app being basic, but functional in its design, participants commented on how they could transfer their learning and improved listening self-efficacy into the real world in challenging listening situations, both socially and in the work-place. Using HELIX had provided

a space where participants were able to take time to learn and reflect about their listening behaviours. This included implementing different behavioural strategies, such as removing distractions or physical changes such as purchasing different headphones to improve clarity by reducing noise. Using HELIX has also aided in fostering awareness about difficulties in hearing in background noise that require different communication tactics, such as asking speakers to adjust their conversational tone when in a noisy environment.

Funnily enough, I had that in reality last night, my daughter was trying to talk to me and whilst we were waiting for the cinema to start and the trailers were quite loud and I was thinking I can't do both of these, I need to choose one or the other. (P30)

I need to have peace and quiet...I'm going to look at getting better earphones for work...Also the other thing is to be a bit bolder in coming back to people and saying either can you say that again or just saying actually I've even said from the outset I can't hear very well in this noisy thing, can you slow down...I suppose I'm not ashamed of the fact that I need people to accommodate me too. (P26)

Repetition obstructed engagement

Despite reporting initial enjoyment from using HELIX, participants found that as time went on the limited content became too repetitive. Whilst some participants reported that the repetitive nature actually made the tasks easier, which boosted their confidence, the majority felt it was detrimental.

I quite enjoyed it at the start, but then I got a little bit tired after about two weeks, so other than that it was fine.(P13)

Repeat those things regularly so to be honest after four weeks I was pretty bored with it.(P26)

The repetitive nature, mainly due to the limit of 60 tasks, was felt to reduce motivation, engagement and to deviate from the actual nature of the tasks.

Once you knew the answers after a couple of weeks it was pointless (P2)

I remember this and then it's like you got a bit complacent until the end, I know this so I'm not listening as well. (P12)

If I couldn't hear it properly I could remember what the answer was and then I felt I was cheating, because I was sort of remembering it rather than hearing it. (P30)

Easy to incorporate into daily life

Participants positively identified that the allocated 10 minute play time was easy to build in around their normal daytime activities, regardless if they were in work or retired. It was reported that this was the right amount of time to maintain concentration and focus, whilst still feeling a sense of achievement.

I just did it when I got home after I'd had something to eat so it was in the evening so it wasn't any trouble at all. (P1)

Probably for me, spot on. I think 10 minutes is not a lot of time, I think if it was any shorter I don't think you'd learn very much from it and I think if it's any longer people would lose interest in it. (P2)

I thought I'm sitting here let's plough on and see how it goes, but equally I don't work, I do a lot of other stuff, but I don't work so I imagine that if I was still working I would prefer the 10 minute bursts. (P23)

In some cases participants felt that HELIX was a daily task that they would like to continue with in the future.

I'd possibly be buying it, but I'd definitely be downloading it if it was free. (P56)

Improved scoring system required to be motivational

As common in training games, HELIX provided a daily and best score, however participants felt that this was either unclear or irrelevant to their needs.

I stopped looking at the score after a while because I couldn't see how the score related to what was going on. (P22).

The concept of using a score was welcomed by participants, but they felt it needed to be clearer as to what the score meant, how the score could be changed and how their score may relate to their peers - to effectively benchmark them against a norm. It was also important for the score to be clearly visible to players.

I thought the scoring card when I first saw it I thought oh yeah that's good because that made me want to kind of achieve a certain level, then I just thought well actually it doesn't matter does it. (P26)

It would be interesting to know how you're doing in relation to other people of your similar age. (P23)

Quite nice if there was a way of like a daily you know statistics or analysis to keep track...one day that you're really tired that you've had a really bad day and your score goes down just to really you know start to make an association as for why I'm not listening well today. (P3)

5.4 Discussion

5.4.1 Main Findings

The purpose of this study was to evaluate the auditory-cognitive training application HELIX across a range of auditory and cognitive tasks, in addition to self-reported communication

confidence, quality of life and overall usability of the app within a population in mid-life with self-reported concerns about their hearing and/or memory.

The primary objective was to evaluate SiN performance using a newly developed online version of the DTT. Whilst the TG demonstrated an improvement in performance over time that was not seen in the control group, statistical analysis showed that this improvement was not significant between the training group and control group. It is, therefore not possible to say for certain whether using HELIX resulted in this improvement in the DTT in the training group.

On-task learning within the app was observed, participants demonstrated a statistically significant improvement in their SNR scores across the 4-week play period. This concurs with the large body of research in the field, whereas similarly to Henshaw et al.[33] off-task learning in this current study was not detected, unlike other studies in auditory training [24, 68, 3] which saw improvements following training.

One of the secondary objectives was to evaluate cognitive performance via a battery of online cognitive tests. Although HELIX primarily focused on training working and immediate memory, other cognitive domains were assessed to analyse any potential transfer of benefits.

Unlike previous studies evaluating auditory and cognitive training [25], there were no significant improvements in any of the cognitive assessments following use of HELIX. This may be due to the nature of the cognitive task and it not being challenging or targeted enough. Whilst participants reported that they found the auditory tasks challenging, the cognitive task appeared to elicit more frustration due to choosing the images or being too easy. This was also reflected in the UEQ, where the lowest scores were received for stimulation and novelty. There is also a possibility that because the participants for both the training and control group had a concentration of high scores in the cognitive screening tool, indicating near normal cognition, that there may have been less ceiling room to improve cognitive performance. The training and control groups scored on average 93.95 and 93.33 respectively out of 100, whereas the scores for the hearing screen were lower, suggesting the sample had a higher level of hearing impairment compared to cognitive impairment. In the interviews, participants felt they became more aware of their hearing difficulties due to the immersive scenarios and that improvements in the

game-play gave them more confidence in their ability to distinguish the speech stimuli in noise.

An unexpected finding was that the CG significantly worsened in performance over time on the Spatial Span test. This measured working memory and was the seventh test in the battery of nine. Whilst this finding cannot be deemed particularly relevant in the evaluation of HELIX, it is of interest that the training group did not deteriorate over time in a test assessing working memory.

The final quantitative objective was to evaluate communication confidence and quality of life, both of these were conducted through self-report. No significant improvements in either of these measures were reported by the training group, however the findings from the qualitative analysis lend support to participants feeling they had in fact improved in their listening capabilities and made positive behaviour changes in their lives.

5.4.2 Usability

Usability was measured using the UEQ tool. Participants rated their experiences against a number of questions across 6 scales. Perspicuity and efficiency scored well, with highlights being that the application was easy to learn, understandable, easy, efficient, practical, organised and friendly. This lends support to previous research that an auditory-cognitive training application is a low-barrier entry intervention that can be easily accessed by a population in mid-life [89, 34]. One theme from the interviews was that a short period of daily play on HELIX was easy to incorporate into normal routines. This is a positive finding given that one of the potential barriers identified in the participatory design phase was that the demands of daily living may get in the way of using HELIX [27]. From the evaluation in this current study, however this was not deemed to be the case. Participants were instructed to play each scenario at least once, but were then given autonomy to decide which scenarios to play for the remainder of the 4-week play period. This may have been a factor in maintaining motivation, as Henshaw et al. [34] suggest that providing a free choice in which users can select tasks that hold relevance for them can essentially act as an intrinsic motivator for use.

Lower scores were received for the app being exciting, interesting and enjoyable, with the latter skewed negatively towards being annoying. Similarly in the interviews the repetitive nature of the application received negative feedback as it was perceived to be boring. Although a number of participants did feel the repetitive nature improved their confidence in recall, thereby reducing the difficulty and actually acted as a motivator. Given that HELIX was iteratively designed with stakeholders to ensure it was relevant, it is unusual that these items were scored lowly. The authors do acknowledge that the application was of very simple and basic design, initially developed as exploratory research, the elementary design may have been the reason behind the lower scores for excitement and interest. Future investment in the aesthetic design of the app may improve these elements of usability. Despite the rudimentary design of the application, it was still able to promote transferable, positive listening behaviours.

5.4.3 Thematic Analysis

6 themes emerged from the interviews regarding effects on quality of life and usability. Participants felt they became more aware of their hearing difficulties due to the immersive scenarios and that improvements in the game-play gave them more confidence in their ability to distinguish the speech stimuli in noise both in the game and in real-world scenarios. The authors suggest that this was because participants found that playing the application made them think more about their listening habits in realistic environments i.e. when they were actively listening and concentrating and how to maximise their concentration to perform better in noisy situations. This draws parallels with the findings from Talaei-Khoei & Daniel [81] and suggests that participants did perceive a transfer of benefits.

Whilst there were no significant findings in the quantitative measures, this should not detract from the positive qualitative findings and merits of using a participatory design process [27, 34]. Utilising a participatory design approach informed key elements of the game design, such as using multiple scenarios relevant to the daily lives of the intended user group. This kept HELIX simple, realistic and ultimately useful. As suggested by Henshaw et al. [33] using training stimuli that holds relevance to every day listening situations ensures that users maintain a

high level of engagement and motivation to continue. It is important to employ a mixed methodology, which is currently lacking in the field, to capture new insight into how auditory-cognitive training can be used over and above quantitative measures [81].

5.4.4 Limitations

The authors recognise that an opportunity sampling method was employed during an unprecedented lockdown due to the Covid-19 pandemic. Participants actively volunteered to join this study because they had self-reported concerns about their hearing and/or memory. This can be extremely emotive, especially when they have witnessed relatives' quality of life affected by hearing loss or dementia. This recruitment was at a time when socialisation was undergoing severe restrictions. The sample, therefore may have been more motivated than the general population to participate and to improve their hearing and memory, which may be a reason why there was a high compliance in using the application and incentive to improve. Additionally, a passive 'do-nothing' control was used, the authors reflect that using an active control may have impacted on any learning effects in the outcome measures, as utilised by Lai et al. [42].

The outcome measures used in this current study were largely dictated by what was deliverable and credible during the Covid-19 pandemic. This resulted in all measures being completed online. The DTT was used at the three test intervals across the evaluation stage, which may have been susceptible to learning effects. Although the literature is generally consistent in finding that for untrained listeners, there is usually a small and short-lived learning effect that then stabilises quickly. The original development paper by Smits et al [73] suggest that a single practice run is sufficient to prevent any further systematic learning. Other studies using digit triplets suggest that there is a brief acclimatisation in the first run, followed by minimal change thereafter, which suggests there are not any observed ongoing training gains [62]. A limitation of this current study is that no practice lists were included for any of the test intervals. Therefore it may be possible that there was a learning effect each time the participants completed the test. The testing was standardised for all participants (control and training group). Participants were asked to complete the test under the same conditions each

time e.g. headphone type and tablet/phone and the stimulus parameters were kept the same. This included starting SNR, step rules, noise type and presentation mode so any potential learning effects would be expected to have been seen across both groups.

A further limitation and previously discussed in the literature [24], is that the DTT may not be complex enough to detect changes in SiN. The QuickSIN has been shown to successfully detect improved SiN listening following a Listening and Communication Enhancement programme [42]. It would have been preferable to use QuickSIN in a clinical setting as a primary outcome measure, but this was not possible due to imposed restrictions.

Despite these limitations, the DTT, was mobilised into an accessible, online test that participants were able to freely use and did not report any problems. This version of the online DTT was unique in its reporting of results. Traditionally, online versions of the DTT are used by private hearing aid dispensers as a marketing tool to screen end-users' hearing. The result either being either a positive statement about having normal hearing or a more concerned approach suggesting the end user visit the private provider for a full audiological assessment and provision of hearing aids. Whilst the online version used in this thesis does not provide a diagnostic opinion of hearing thresholds, it does provide a users with a way to monitor their performance over time. This has implications for clinical practice, as it provides both the end user and audiologists with a tool to monitor SiN over time via a low-barrier interface. In future, it could be used for people that attend an audiological assessment, but do not meet the threshold for fitting hearing aids. Instead they could monitor their performance over time and re-attend when they feel their ability to detect SiN has depleted, evidenced by the scoresheet the test provides each time. Rather than being used as, what is effectively a marketing ploy by private providers, it could be well-used as a surveillance method.

Less positive usability scores are likely due to the basic task set-up and aesthetic. Future investment in the aesthetic design of the app may improve these elements of usability. It should be recognised that despite the rudimentary design of the application, participants still felt play promoted transferable, positive listening behaviours. Whilst the level of repetition in this current study, was at times deemed an annoyance by users, it also acted as a reference

point and reassurance for some. Any future designs of similar serious games should aim to include an element of repetition with scope to unlock newer content to maintain challenge.

5.4.5 Further Development

There is scope to develop HELIX further, building on the common recommendations of the training group to improve usability and engagement. The main recommendations from the participants were to introduce more variety in content to counteract the negative detractors from repeating the same scenarios. Further scenarios suggested were watching television; asking for directions or using a Sat-Nav; pub or live music; conversational settings with families or friends. There was also a need for varying speakers in the audio stimuli such as male and children's voices. There were recommendations made over the accessibility of HELIX. This version was produced for iOS, so Android users required a loan device. For some participants the images were too small or unclear so there is scope to improve the visual aspect of the tasks. The authors concur that the recommendations would likely encourage continuous play and embed this application into daily routines for maximum impact.

Chapter 6

Conclusion

This chapter provides the final conclusions of the key findings from the participatory design stage and the mixed methods evaluation stage. The lessons learned from both stages are summarised here with suggestions for potential future endeavours to further the knowledge base in this field.

6.1 Summary of Thesis Achievements

The overarching objectives of this thesis were to utilise a participatory design approach to understand the facilitators, barriers and design content for a new auditory-cognitive training application with the intended users being adults at risk of age-related hearing and/or cognitive decline and evaluate said application against a number of outcome measures through a RCT with additional qualitative research methods.

The main objectives have been addressed and findings presented via the two papers presented in Chapters 3 and 5. Due to the unprecedented global pandemic caused by Covid-19, changes to the planned RCT were made with the unexpected and additional contribution of developing a new online version of the DTT, which is work outlined in Chapter 4.

This thesis demonstrates that there is indeed appetite in the intended user group for an

auditory-training application to be readily available if it aligned with their design requirements. Although any improvements against the outcome measures were not statistically significant, the qualitative findings demonstrated that participants did perceive a transfer of benefit and positive behaviour change towards their hearing and memory.

The key findings from the participatory design phase included ensuring the content shared congruence with their hobbies, was accessible, provided enough motivational challenge, provoked an element of addictive competition and had a more realistic design aesthetic. It should also overcome the main foreseen barrier of other demands of life getting in the way of playing it. Utilising a participatory design ensured that the subsequent auditory-training application that was developed - HELIX, was well-adopted by the training group and scored well in usability.

The key findings from the evaluation stage via the RCT showed an improvement in the performance of the DTT, measured at four and eight weeks after the baseline within the TG, that was not present in the CG. Although this improvement was not significant between the two groups, so it is not possible to say with conviction that the improvement was as a result of using HELIX.

On-task learning, as expected, did occur with the TG significantly improving in their ability to complete the tasks at less favourable SNR at the end of the 4 week play period, compared to the start. Whilst no other off-task improvements were seen in the cognitive test battery or self-report questionnaires, this thesis does contribute a strong qualitative element, which has been notably lacking in this field.

Three themes emerged from the qualitative arm of the evaluation which suggested use of HELIX over the relatively short space of play time of 4 weeks, prompted participants to have a greater realisation of their hearing and/or memory difficulties and actions needed, gave them an improved listening and recall self-efficacy and encouraged positive behaviour change. Despite not detecting any quantitative improvements, participants themselves reported significant improvements to their daily life, not just during the 4 week test period, but changes that they committed to taking forward.

From a design perspective, participants expressed views that were collated into three themes around usability to compliment the findings from the validated UEQ, designed to measure different aspects of usability. Whilst HELIX scored positively for attractiveness, perspicuity, efficiency and dependability; more neutral scores were reflected for stimulation and novelty. These findings were repeated in the qualitative thematic analysis, as participants felt the restricted number of levels meant there was a lot of repetition during the playing time, which in turn obstructed engagement and contributed to reduced motivation. In contrast participants did feel that HELIX was easy to incorporate into daily life, which was the only potential barrier foreseen in the original participatory design process. Given this was one of the final themes to emerge, it can be said with confidence that HELIX did indeed overcome the barrier to adoption in the target user group.

Ultimately this thesis underlines the importance that adopting a co-design approach can have on the usability, acceptability and adoption of a new auditory-cognitive training application. In using this approach HELIX was able to act as a vehicle for positive behaviour change for the participants that played it on a daily basis for a short 4 week period and enhances understanding in how to co-design and develop a training application that be utilised by other developers not just in this field but in using serious games as agents for health behaviour change for any long-term condition. Nevertheless there have been lessons learned which can be taken forward into the field by either developing HELIX further, or by offering insight to other developers in this particular field.

6.2 Limitations

The deployment of the RCT was heavily disrupted and restricted due to the Covid-19 pandemic; it did however, prompt the unexpected development of a new, online version of the DTT which is also now freely available for use and provided an opportunity to pivot towards delivering a fully remote trial which allowed a greater diversity in the patient sample to be recruited. Whilst the author endeavoured to recruit a diverse sample in the participatory design phase, on reflection

given the geographical location of the research, the co-design group was London-centric and due to the opportunistic sampling method used, included hearing aid wearers, who were not the intended final users. This may have impacted on how stakeholders felt they would use the application, for instance commuting on the tube. This was not necessarily reflected when wider geographical recruitment was conducted in the RCT, as whilst participants commented that they would easily incorporate the game into daily life, this was often when they were home from work using different modes of transport to commute, such as driving or walking. This thesis demonstrates the merits of using co-design, but with hindsight a wider pool of stakeholders may have yielded a more holistic view of how the application might be used by a wider target user group.

The lack of interaction that was imposed on participants during the pandemic may have prompted more motivation in the participant samples. Recruitment was completed at a time when socialisation was still heavily restricted and the public were being advised to stay at home or within their bubble. Without repeating the trial outside of those restrictions, it is not possible to say whether the living conditions at the time, affected motivation to participate in research by providing a purpose or achievement goal. Not using a passive, do-nothing control group, eliminated further analysis on potential learning effects within each outcome measure.

The types of outcome measures used were effectively dictated by the pandemic and subsequent recovery. All measures had to be redesigned to be delivered online, which for some of the self-report questionnaires was relatively straightforward, but for the SiN it meant deploying a less complex test via the DTT. It would have been preferable to use QuickSIN as the primary outcome measure, as it may have been more sensitive to detecting changes over time. Using a clinically validated outcome measure, such as the SIN may have yielded statistically significant changes between groups that the DTT was not capable of detecting.

6.3 Future Work and Implications for Clinical Practice

The design of the application itself was simple and originally deemed as exploratory research to test the concept of co-designing and using an auditory-training application which has been achieved. It is suggested that future work could focus on the elements highlighted by participants around the stimulation and novelty that a similar application could provide through improved design, more variety in stimuli and expanded content to avoid repeating the same six scenarios. Participants suggested different scenarios could include situations such as an airport, exercise class and a restaurant.

Even though HELIX did employ a rudimentary design, adoption was high, with participants demonstrating daily play and on-task learning demonstrating that the use of an auditory-cognitive training application was indeed a low-barrier entry opportunity. It is unknown whether the adoption would continue for a prolonged period of time than the required 4 week play period, so future work could explore the use of an application over a longer period of time but it would need to have more content to sustain interest over a sustained period.

There is also the opportunity to utilise different outcome measures that may be more robust in differentiating changes in SiN. Whilst the evaluation originally planned to use the QuickSIN test, it was not possible due to imposed restrictions. Now that these restrictions have been lifted there is scope to revisit the use of SiN tests in both a clinical and research capacity.

Speech testing is not commonly used in NHS practice due to the time constraints on hearing assessments. It is deployed usually when there is a discrepancy between hearing aid programming and patient performance indicating a potential undetected processing issue, or as a counselling tool when hearing aid users with poor speech discrimination have unrealistic expectations on how a hearing aid can perform within noisy environments. There is a place, however to potentially use an online SiN test, such as the DTT to effectively screen patients who fit a similar profile to the participants in this trial. Those that feel they have some hearing complaints in noise, but do not want to wear or do not need to wear traditional hearing aids. Those with good test performance can be given information, whilst those who score poorly could be given

a program of auditory training, if more application based programs existed and were free at the point of access. The purpose of the DTT in this thesis was to monitor changes over time, there is no reason a similar process could not be implemented in clinical practice to allow patients or potential patients to monitor their ability outside of a traditional audiology clinician-led service. If users then found a decline over time, this could then trigger a referral for full audiological assessment and give the clinician insight into the specific issues a patient may be experiencing with SiN, that they would not necessarily have access to as part of a routine clinic.

Whilst the design and evaluation of HELIX was not primarily intended to influence current clinical practice, the findings highlight important concepts with potential clinical relevance. While most participants did not report a diagnosed hearing impairment or previous consultation with their general practitioner, engaging with HELIX in the context of hearing and memory training brought their hearing health to the forefront of awareness. The provision of information and discussion around hearing needs and communication strategies encouraged deeper reflection, prompting some to consider whether a formal hearing assessment might be appropriate.

For clinicians, this suggests that online tools such as DTT or applications such as HELIX, could motivate a broader and more diverse group of individuals to seek advice and assessment earlier in the course of age-related hearing loss. Even when hearing aids are not immediately prescribed, platforms such as these would provide early engagement, demystify the process, normalize help-seeking, and offer a low-barrier pathway for individuals to engage with hearing care as their needs evolve in the future.

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Appendix A: Participatory Design Round 1 Topic Guides

Topic Guide

Before the focus group starts:

- Check all participants have read and understood the participant information sheets and signed the consent form.
- Remind them that participation is voluntary and that they can withdraw at any time.

Explain the ground rules for the session:

- This is a respectful discussion and everyone's opinions are valid, so it is important to not interrupt each other or talk over one another.
- Anything said in the focus group is to remain confidential. The session will be audio recorded, however participants will not be identifiable as participant numbers will be used.
- Participants are free to ask questions or take breaks at any time they wish.

Start of focus group:

My name is Emily and I will be facilitating the discussion. Please can everyone introduce themselves to the group.

I will give brief overview of the project and what it is that we will be discussing today. The research project is looking at the relationship between aged-related hearing loss and developing problems with memory and attention, which may then lead onto dementia. To do so, the project is looking to design and develop a brand new application that can be played on mobile phones or tablets that can provide training for hearing, memory and attention. This project is part of my PhD and I want to explore and discuss views and attitudes towards using an application or game and how best to design the game to make sure it is appropriate and fun for the users.

I have some questions related to this idea which will help guide our discussion. I am interested in finding out what you honestly think.

Warm-Up questions:

- How important is your physical health to you and your patients?
- How important is your mental health to you and your patients?
 - Is this any different to physical health?

- Where would you suggest patients find advice on their physical and mental health?

Section 1 – Hearing and Dementia

- How important is it for your patients to have good hearing and a good memory?
- Are you aware of hearing loss and dementia being linked?
 - Are your patients aware?
 - Would you discuss this link with them?
- Do you think we encourage our patients to look after their hearing and memory well enough?
- If your patients had concerns over their hearing or their memory, what would you advise them to do?
 - Where would you tell them to look for information?
 - Would you communicate this to other medical professionals?
- Do you currently recommend any learning or training material for your patients' hearing and memory?
 - Websites?
 - Organisations?
 - Apps?
 - Groups?

Section 2 – Using Technology

- Do you own a smartphone or tablet
 - If yes, why?
 - If no, why not?
- How do these devices help or hinder us in our daily lives?
- Do you think you utilise technology in your clinical practice?
 - Are you aware of anything particular that you feel is useful?
 - Anything that isn't useful? If so why?
- How useful could apps be for healthcare in the future?
 - Is there anything in particular you think would be useful?

- What do you foresee as barriers to your patients accessing and using an app?
- What do you foresee as potential gains to your patients accessing and using an app?

Section 3 – Designing the Application

Action – Demonstrate ‘Sea Hero Quest’ app and explain the purpose and popularity.

- What do you think of the app?
- What do you like and dislike about the app?
- What would make a good app for people aged 50 and over to play?
- Thinking about hearing and memory, what tasks do you think your patients would like to complete in the app?
- What would make you want to recommend an app to your patients?
 - Would you like it to be realistic or more of a game?
- Would you prefer for the patient to use the app on their own or would you prefer they use it with other people?
 - Guide or advisor?
 - 2nd player online?
 - In your clinics?
- Does anyone have any further questions or comments to make?

After the group has finished:

- Thank everyone for participating and volunteering their time.
- Explain what will happen next e.g transcription, formalising a report to the developer, developer to start of first prototype.
- Explain when the next focus group will be and check participants are happy to continue and attend the next group.
- Remain in the room in case participants would like to discuss any particular concerns. Highlight the leaflets regarding hearing loss, dementia and how to seek help if concerned.
- Ensure participants leave with a copy of the participant information sheet and consent form.

Topic Guide

Before the focus group starts:

- Check all participants have read and understood the participant information sheets and signed the consent form.
- Remind them that participation is voluntary and that they can withdraw at any time.

Explain the ground rules for the session:

- This is a respectful discussion and everyone's opinions are valid, so it is important to not interrupt each other or talk over one another.
- Anything said in the focus group is to remain confidential. The session will be audio recorded, however participants will not be identifiable as participant numbers will be used.
- Participants are free to ask questions or take breaks at any time they wish.

Start of focus group:

My name is Emily and I will be facilitating the discussion. Please can everyone introduce themselves to the group.

I will give brief overview of the project and what it is that we will be discussing today. The research project is looking at the relationship between aged-related hearing loss and developing problems with memory and attention, which may then lead onto dementia. To do so, the project is looking to design and develop a brand new application that can be played on mobile phones or tablets that can provide training for hearing, memory and attention. This project is part of my PhD and I want to explore and discuss views and attitudes towards using an application or game and how best to design the game to make sure it is appropriate and fun for the users.

I have some questions related to this idea which will help guide our discussion. I am interested in finding out what you honestly think.

Warm-Up questions:

- How important is your physical health to you?
- How important is your mental health to you?
 - Is this any different to your physical health?
- How often would you see your GP for advice?

- Would you seek advice or information elsewhere? Where?

Section 1 – Hearing and Dementia

- How important is your hearing to you?
- Are you aware of hearing loss and dementia being linked?
- Do you think we look after our hearing and memory well enough?
- If you had concerns over your hearing or your memory, what would you do?
 - Where would you look for information?
 - Who would you tell?

Section 2 – Using Technology

- Do you own a smartphone or tablet
 - If yes, why?
 - If no, why not?
- How do these devices help or hinder us in our daily lives?
- How useful could apps be for healthcare in the future?

Section 3 – Designing the Application

Action – Demonstrate ‘Sea Hero Quest’ app and explain the purpose and popularity.

- What do you think of the app?
- What do you like and dislike about the app?
- What would make a good app for people aged 50 and over to play?
- Thinking about hearing and memory, what tasks would you like to complete in the app?

- What would make you want to use the app every day?
 - Would you like it to be realistic or more of a game?
- Would you prefer to use the app on your own or would you prefer to use it with other people?
 - Guide or advisor?
 - 2nd player online?
- Does anyone have any further questions or comments to make?

After the group has finished:

- Thank everyone for participating and volunteering their time.
- Explain what will happen next e.g transcription, formalising a report to the developer, developer to start of first prototype.
- Explain when the next focus group will be and check participants are happy to continue and attend the next group.
- Remain in the room in case participants would like to discuss any particular concerns. Highlight the leaflets regarding hearing loss, dementia and how to seek help if concerned.
- Ensure participants leave with a copy of the participant information sheet and consent form.

Appendix B: Participatory Design Round 2 Topic Guides

Round 2 - Topic Guide – Professionals

Before the focus group starts:

- Check all participants have read and understood the participant information sheets and signed the consent form.
- Remind them that participation is voluntary and that they can withdraw at any time.

Explain the ground rules for the session:

- This is a respectful discussion and everyone's opinions are valid, so it is important to not interrupt each other or talk over one another.
- Anything said in the focus group is to remain confidential. The session will be audio recorded, however participants will not be identifiable as participant numbers will be used.
- Participants are free to ask questions or take breaks at any time they wish.

Start of focus group:

My name is Emily and I will be facilitating the discussion. Please can everyone introduce themselves to the group.

I will give brief overview of the project and what it is that we will be discussing today. The research project is looking at the relationship between aged-related hearing loss and developing problems with memory and attention, which may then lead onto dementia. To do so, the project is looking to design and develop a brand new application that can be played on mobile phones or tablets that can provide training for hearing, memory and attention. This project is part of my PhD and I want to explore and discuss views and attitudes towards using an application or game and how best to design the game to make sure it is appropriate and fun for the users.

I have some questions related to this idea which will help guide our discussion. I am interested in finding out what you honestly think.

Using digital games:

- Do you think your patients ever use digital games or gaming apps?
 - How often do you use digital games?
 - What games do you think they play?
 - What do you think they like about these games?

- What do you think they dislike about these games?
- What motivates them to play these games?
- Do you think your patients use apps?
- Which apps do you think your patients may use the most?
- Do you currently recommend any auditory or cognitive training games to your patients?
 - Why? Which ones? How do patients react?
 - Why not?

Looking at the alpha version of the app:

Context:

- Are the situations shown in the app relevant to the daily lives of people with hearing loss?
- What sounds would make the environment sound like the real place?
- What other situations do you think would work well as a game?
 - Why?

Concept:

- Do you think these sorts of challenges in the game would provide the right level of difficulty?
- Would the game help to increase your patients' confidence in their hearing in noise OR their short-term memory?
- Would you prefer your patients to play the game alone or under supervision in the clinic?
- Do you think the scenario e.g café should change?
- Do you think patients would prefer a customised scenario?

Playability:

- Would you use this game? Or recommend it to your patients?
 - How often would you recommend they play this game?
 - What would motivate your patients to play it?

- What would prevent your patients from playing it?
 - Do you think nudge notifications would work?
 - What sort of incentives would encourage you or your patients to play the game?
 - Would it be helpful for you to receive information on the scoring for your patients?
 - Could you see this being a tool to be used in patient's rehabilitation or counselling?
- What device would you or your patients prefer to play this game on?
 - How do you think the instructions should be given?
 - Do you prefer pictures or words for the buttons?

Round 2 - Topic Guide – Service Users/Volunteers

Before the focus group starts:

- Check all participants have read and understood the participant information sheets and signed the consent form.
- Remind them that participation is voluntary and that they can withdraw at any time.

Explain the ground rules for the session:

- This is a respectful discussion and everyone's opinions are valid, so it is important to not interrupt each other or talk over one another.
- Anything said in the focus group is to remain confidential. The session will be audio recorded, however participants will not be identifiable as participant numbers will be used.
- Participants are free to ask questions or take breaks at any time they wish.

Start of focus group:

My name is Emily and I will be facilitating the discussion. Please can everyone introduce themselves to the group.

I will give brief overview of the project and what it is that we will be discussing today. The research project is looking at the relationship between aged-related hearing loss and developing problems with memory and attention, which may then lead onto dementia. To do so, the project is looking to design and develop a brand new application that can be played on mobile phones or tablets that can provide training for hearing, memory and attention. This project is part of my PhD and I want to explore and discuss views and attitudes towards using an application or game and how best to design the game to make sure it is appropriate and fun for the users.

I have some questions related to this idea which will help guide our discussion. I am interested in finding out what you honestly think.

Warm-up Questions:

- What are your main hobbies or interests?
- What motivates you to take part in these hobbies?
- What prevents you from taking part in these hobbies?
- Do you prefer physical or mental hobbies?
 - Why?

Using digital games:

- Have you ever used digital games or gaming apps before?
 - How often do you use digital games?
 - What games do you play?
 - Do you play traditional games? E.g chess, board games, jigsaws?
 - What do you like about these games?
 - What motivates you to play these games?
 - Do you pay for apps/games?
 - How do you decide which apps to download?
 - What do you dislike about these games?
 - What prevents you from playing these games?
 - What prevents you from playing these games for a long period of time?
 - Who do you play digital games with?

Looking at the alpha version of the app:

Context:

- Are the situations shown in the app relevant to the daily lives of people with hearing loss?
- What sound would make the environment sound like the real place?
- What other situations do you think would work well as a game?

Concept:

- Do you think these sorts of challenges in the game would provide the right level of difficulty?
- Would the game help to increase your confidence with your hearing in noise OR your short-term memory?
- Would you prefer to play the game alone or under supervision in the clinic?
- Would you like the scenario e.g café to change?
- Would you prefer a customised scenario?

Playability:

- Would you use this game?
 - How often would you play this game?
 - What time of day would you play the game?
 - What would motivate you to play it?
 - Would you like to receive nudges?
 - What sort of incentives would encourage you to play the game?
 - What would motivate you to play this game for a long period of time?
 - Would you like to play this game with other people?
- What device would you prefer to play this game on?
 - Would you play this with headphones?
- How would you like to receive the instructions?
- Do you prefer pictures or words for the buttons?

Appendix C: Evaluation Topic Guide

Topic Guide for Exit Interview

Before the interview starts:

- Remind them that participation is voluntary and that they can withdraw at any time.

Explain the ground rules for the session:

- This is a respectful discussion and everyone's opinions are valid, so it is important to not interrupt each other or talk over one another.
- Anything said in the interview is to remain confidential. The session will be audio recorded, however participants will not be identifiable as participant numbers will be used.
- Participants are free to ask questions or take breaks at any time they wish.

Start of interview:

My name is Emily and I will be facilitating the discussion. Please could you both introduce yourselves.

Thank you for participating so far in the project, we are now at the end of training phase so I would like to take this opportunity to obtain feedback from your experiences across the project and with the application. After this session I would like to invite you back in approximately 4-week's time for a follow-up session to repeat the tests for a final time.

I will remind you of the aim of the project. The objective of the application is to provide training at home for hearing speech in noise and memory, with an aim to improve hearing in noise, cognition, communication and quality of life in a fun, engaging and useful way.

- To what extent do you agree with the following statement:
 - My experience of the app matches the aim of the app?
- What did you learn about your own hearing and memory whilst using the app?
- Do you feel any differently about your hearing and memory that you did before using the app?
- Were you able to use the app and the headphones?
 - Did you understand what to do?
 - Were the instructions clear?
- What did you like about the app?
 - Did you like the way it looked?
 - Did you like the sounds/images used in the app?
 - Was it easy to interact with e.g using the buttons and menus?
 - Did you like the rewards given?
 - Did you find it fun to use?
- Did the app give you enough feedback on your progress?

- Were the levels shown in the app relevant to your daily life?
- Did the levels provide the right level of difficulty?
- Are there any other challenges that could have been included/
- Has playing the game increased your confidence in being able to improve your hearing, communication and memory?
- What didn't you like about the app?
 - Did you have any problems playing the app?
 - Did you find anything frustrating when using the app?
- How do you think the app could be improved?
- Do you have any further comments that have not been covered?

Appendix D: Proof of Permission to Reproduce Published Work



JMIR Editorial Team (JMIR Publications)

May 26, 2022, 16:44 EDT

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Thank you for reaching out. Authors of articles published by JMIR Publications do not need our permission to use part or all of an article in their thesis or book. For more information on this, I have linked one of our KB articles below,

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Frost, Emily J

May 23, 2022, 07:30 EDT

Dear Editorial Support,

I authored a paper that you published in
2020 <https://humanfactors.jmir.org/2020/3/e19880/> doi:
10.2196/19880<<https://doi.org/10.2196/19880>>.

It is part of my PhD project and I would like to use the paper in my final thesis.

Could I request permission to include this in my thesis?

Many thanks
Emily