An Investigation of the Gamification of Rehabilitation for Visually Induced Dizziness

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Thesis Summary

Visually induced dizziness is vertigo or dizziness that is triggered by a complex, large field, or moving visual stimulus (Bisdorff et al., 2015; Staab, 2023). Current forms of rehabilitation can be effective but have issues with adherence (Pavlou et al., 2013), have barriers to accessibility (Mandour et al., 2021; Xie et al., 2021), do not work on all people with visually induced dizziness (Pavlou et al., 2004), or a combination of all three. This thesis develops and tests the gamification of visual desensitisation rehabilitation in order to solve these identified issues of rehabilitative promise, accessibility, and motivation. The development of the tool, named Balance-Land, is achieved through user-centred design (Abras et al., 2004), iteratively changing Balance-Land based upon feedback from people with visually induced dizziness and clinicians (Chapters 2, 3, and 6). The first large-scale feasibility study of Balance-Land (Chapter 4) recruited participants globally and aimed to explore ecologically valid adherence, usability, and the relationship between symptom improvement and time spent using Balance-Land. Exploring the play-pattern data from the feasibility study, Chapter 5 uses linear mixed models to examine the factors associated with the daily symptoms and daily play duration of participants. Qualitative data from participants involved in the feasibility study were assessed, improvements to Balance-Land prioritised, and a final round of feedback from audio vestibular clinicians assessing their impact, were made in Chapter 6. The end result was Balance-Land: a new tool for visual desensitisation rehabilitation for people with visually induced dizziness, that can be downloaded and played for 100 megabytes anywhere in the world.

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Acknowledgements

For Bonny. He was my light.

1 Chapter 1: General Introduction

1.1 What is visually induced dizziness?

Visually induced dizziness is vertigo or dizziness that is triggered by a complex, large field, or moving visual stimulus (Bisdorff et al., 2015; Staab, 2023). Vertigo describes the sensation that you or yourself are moving, despite no actual movements, while dizziness describes a range of sensations related to impaired spatial orientation, without the distorted sense of motion (Bisdorff et al., 2015). Whilst the symptoms of visually induced dizziness are characterised by their visual triggers, what causes them varies from person-to-person, and as such a situation one finds intolerable another can find tolerable (Staab, 2023; Staab et al., 2017). Visually induced dizziness has many different names and for the purpose of this thesis, optokinetic motion sickness, visual vertigo and visually induced vertigo will all be referred to as visually induced dizziness. Gamble (2022) conducted interpretative phenomenological analysis (Eatough & Smith, 2017) - which is a type of qualitative analysis focusing on personal lived experiences - on six people with visually induced dizziness. Quotes from their lived experiences have been used to highlight the effect visually induced dizziness has on a person life.

Figure 1 shows four common situations that would often trigger symptoms of visually induced dizziness. Figure 1A is an example of repeating patterns, particularly those with high contrast and high spatial frequencies. Real world environments with patterned carpets or wallpapers are particularly problematic for people with visually induced dizziness because the optic flow created when moving past these patterns creates an intense visual motion cue. Figure 1B contains moving stimuli (people moving in crowds). These moving stimuli can create situations of visual-vestibular conflict where the visual system is relaying global motion signals, while the vestibular system might be indicating the individual is not moving. Figure 1C will typically involve bright lights and flicker. People with visually induced dizziness can have high visual sensitivity and visual stress (Pavlou et al., 2007; Powell, Derry-Sumner, Shelton, et al., 2020), and many also have migraine (Eggers et al., 2014). Fluorescent lighting and flickering lights (e.g. sunlight flashing through trees) can also simulate visual motion. Figure 1D is a supermarket – an intense visual environment that combines all these factors and is often a feared location for people with visually induced dizziness. So much so that the condition was once known as Supermarket Syndrome (McCabe, 1975). Shopping centres, nightclubs, and others such intense visual environments are similarly problematic:

"It's worse when I'm out the house cause so much is going on so much is moving – traffic, people, crowds erm too much things to look at in a supermarket you know when you've got rows and rows of things it's just too much (…) It's too much, it's too much erm too much visual information almost" (Sian: 134-136; 141, (Gamble, 2022)

Living with symptoms of visually-induced dizziness can have a debilitating impact on people's lives and ability to function (Gamble, 2022). Some patients also report feeling dismissed when they go to speak to their health practitioners about their symptoms:

"Like the doctors were [emphasised] so rude like some of them it was so bad it was because I'd been in a couple of times about something before and I think it was just like 'oh she's, it's just this anxious woman just keeps coming in'." (Lara: 246-249)

And *"I felt like I lost my identity. Completely."* (Lara 585, (Gamble, 2022)).

Figure 1, Examples of situations that trigger VID. Top left is a living room with a visually stimulating pattern that is repeated. Top right is a crowded shopping centre, with many bright, noisy, moving people. Bottom left is a cinema, the dark environment with the majority of visual space being taken up by a screen can be extremely triggering. Bottom right is a supermarket, note the straight lines, colour, and luminance.

1.2 Associated Conditions and Treatment Options

Visually induced dizziness often develops as an acute or chronic symptom of another vestibular condition. Common associated conditions include: persistent perceptual postural dizziness (PPPD), a functional form of chronic dizziness; vestibular migraine, a migraine which can cause vestibular or balance symptoms and sometimes may present without an actual headache; vestibular neuritis, which is an inner ear disorder that can cause vertigo, dizziness, balance issues, nausea, and vomiting; and Ménière’s disease, an inner ear condition that affects balance and hearing (Arshad et al., 2023; Best et al., 2009; Bruderer et al., 2017; Dieterich et al., 2016; Dieterich & Staab, 2017; Kim et al., 2023; Popkirov, Staab, et al., 2018; Staab et al., 2017; Thomson, 2017).

Visually induced dizziness is more common in females (2:1 ratio) (Formeister et al., 2018; Ruckenstein & Staab, 2009) and in middle age (Dieterich et al., 2016; Neuhauser, 2016; Strupp, 2003). There also seems to be a complex relationship with anxiety, where anxiety can be a predisposing, maintaining, and consequential factor (Staab, 2023; Staab et al., 2017) and, for best patient outcomes, must also be treated along with visually induced dizziness symptoms (Popkirov, Stone, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023).

1.2.1 A History of Visually Induced Dizziness

Historical observations that described something similar to the visually induced dizziness we know today can be traced back to the 1800s (Benedikt, 1870; Cordes, 1872; Westphal, 1871) with the first report of "visual vertigo" occurring in 1797 (Balaban & Jacob, 2001). The German psychiatrist Carl Westphal (1871) coined the term agoraphobia or 'fear (phobia) or the marketplace (agora)'. Although part of this fear might have been a fear of open spaces or a social anxiety, some of the symptoms may also have been dizziness related. A century later, McCabe (1975) coined the term 'Supermarket syndrome' to describe visually induced dizziness, particularly in intense environments such as shopping centres (see Figure 1D). Bronstein (1995) noted around 1 in 3 patients have persistent visually induced dizziness after recovery of an acute vestibular insult and termed this symptom "visual vertigo".

Others came to describe a similar groups of symptoms as: phobic postural vertigo (Brandt & Brandt, 2003); chronic subjective dizziness (Ruckenstein & Staab, 2009); and space and motion discomfort (Jacob et al., 2009). All four of these conditions have visually induced dizziness as a core symptom and notice other commonalities such as persistence of visually induced dizziness, complex visual stimuli acting as precipitating factors, and anxiety either being required (e.g. phobic postural vertigo) or commonly found as co-occurring. Some highlight demographic imbalances in diagnoses (e.g. chronic subjective dizziness 70% female), although note that any gender or age can be diagnosed. In 2017, these associated symptoms and conditions were combined into one diagnosis: persistent postural perceptual dizziness or PPPD (Staab et al., 2017), which found visually induced dizziness as a core component of the diagnosis, along with anxiety.

Visually induced dizziness symptoms also occur in the general population, on a spectrum with about 10% of the general population scoring above the 25th percentile patient score for people with PPPD (Powell, Derry-Sumner, Rajenderkumar, et al., 2020). Visually induced dizziness is a layer 1 condition according to the ICVD (International Classification of Vestibular Disorders) (Bisdorff et al., 2015) and is found in many disorders and diseases such as persistent perceptual postural dizziness (PPPD), vestibular migraine, vestibular neuritis, and Ménière's disease (Arshad et al., 2023; Best et al., 2009; Bruderer et al., 2017; Dieterich et al., 2016; Dieterich & Staab, 2017; Kim et al., 2023; Popkirov, Staab, et al., 2018; Staab et al., 2017; Thomson, 2017).

There has been a persistent issue in the literature of confusing symptoms of visually provoked dizziness (under many names) with a diagnosis of a vestibular disorder (under overlapping names). For example, Bronstein (1995) coined the term "visual vertigo" and then people were given this as a diagnosis until it was combined with PPPD. However, there were also symptoms called "visual vertigo" which can be associated with multiple conditions and categorised via questionnaires such as the Visual Vertigo Analogue Scale (VVAS) (Dannenbaum et al., 2011).

This confusion persisted within the literature, and created dilemmas for research, such as whether patients with migraine should be included or excluded from studies of visual vertigo. The shift to 'visually induced dizziness or vertigo' by the vestibular society in 2015 (Bisdorff et al., 2015) aimed to shift references of *visual vertigo the symptom* away from *visual vertigo the diagnosis*. The classification of PPPD in 2017 (Staab et al., 2017) then provided a new name for *visual vertigo the diagnosis* and notably includes movement and postural elements which are absent from visual vertigo the symptom. This move also catalysed research in PPPD, but at the same time perhaps lost sight of the additional association of visually induced dizziness with migraine, Ménière's Disease and other vestibular disorders. For example, Powell et al. (2020) described the VVAS scale as 'symptoms of PPPD', whereas we would now prefer to use the more general term *'visually induced dizziness'* to describe the symptoms it asks about.

As a result of all this, research in this field inherits a potentially confusing history of how symptoms and diagnoses have been labelled. Here we take a symptom-based approach focussing on visually induced dizziness – the experience of dizziness provoked by visual stimuli - regardless of what diagnosis it is associated with. We assume that visual desensitisation is aimed at visually induced dizziness – the symptom – rather than a specific condition such as PPPD. As such, it is unlikely to be effective at mitigating the other symptoms of a diagnosis, such as the postural or movement elements of PPPD or tinnitus in Ménière's Disease.

1.2.2 Persistent Postural Perceptual Dizziness (PPPD)

We are interested in visually induced dizziness, which as previously described, is best considered a symptom that appears within a number of conditions. However, Persistent Postural Perceptual Dizziness (PPPD or 3PD), is one of the conditions which is most characterised by visually induced dizziness and where it can be most chronic, impactful, and difficult to rehabilitate. PPPD was recently classified in 2017 (Staab et al., 2017), from four prior, separate, diagnoses: Visual Vertigo (Bronstein, 1995); Phobic Postural Vertigo (Brandt & Brandt, 2003); chronic subject dizziness (Ruckenstein & Staab, 2009); and space and motion discomfort (Jacob et al., 2009). PPPD is most prevalent in middle-aged women (Dieterich et al., 2016; Neuhauser, 2016; Strupp, 2003), although people from all ages and walks of life can be affected. Not all people will experience the symptoms of PPPD with the same intensity, or in the same manner, as with visually induced dizziness. However, there appears to be some situations that people consistently report always triggering their symptoms, as they contain such a large concentration of triggers each person will find at least one; a commonly cited example is the supermarket and busy moving traffic (McCabe, 1975; Söhsten et al., 2016; Staab, 2023; Staab et al., 2017).

As shown by the diagnostic criteria in Staab et al. (2017), visually induced dizziness in PPPD must be exacerbated by three factors: upright posture, active or passive motion, and exposure to moving visual stimuli/complex visual patterns (Staab et al., 2017). These symptoms do not need to be present at all times but do need to occur at least half of the time (most days) for a PPPD diagnosis to occur. As a result, getting diagnosed with PPPD can be a difficult task whilst all other potential causes must be investigated due to criterion E of the diagnosis criteria from Staab et al. (2017): *the symptoms may not be better explained by another diagnosis* (Staab et al., 2017). This often means that getting a PPPD diagnosis takes time. We must note, however, that PPPD is not a diagnosis of exclusion and does still require all other criteria to be a valid diagnosis. Many people with PPPD have comorbid anxiety (Guerraz et al., 2001; Staab et al., 2017; Trinidade, Cabreira, Kaski, et al., 2023; Zur et al., 2015). There is a growing understanding of the link between anxiety and

PPPD, with recent research finding preexisting anxiety as a predictor of PPPD or PPPD-like dizziness (Trinidade, Cabreira, Goebel, et al., 2023)

1.2.3 Vestibular Neuritis

Visually induced dizziness is found in vestibular neuritis (Arshad et al., 2023; Best et al., 2009; Godemann et al., 2005). The aetiology of vestibular neuritis has not been completely established; however, it has been thought to result from inflammation of the vestibular nerve, classified as an acute peripheral vestibulopathy (Walker, 2009) and is the third most common peripheral vestibular disorder (Bae et al., 2022). The incidence of vestibular neuritis is around 3.5 to 15.5 per 100’000 people (Strupp & Magnusson, 2015; Wiener-Vacher et al., 2018), and it is more common in females (2:1) (Hülse et al., 2019). After an acute vestibular neuritis episode, around 50% of people will report long term vestibular symptoms (Cousins et al., 2014) and it is one of the main precipitating condition associated with PPPD. Visually induced dizziness is common during an episode of vestibular neuritis; however, the main concern is the potential for the development of chronic functional dizziness after the acute neuritis has resolved. People with increased visual dependence during their vestibular neuritis - a reliance on vision for postural stability (Maire et al., 2017) - are more likely to develop PPPD-like chronic dizziness (Trinidade, Cabreira, Goebel, et al., 2023).

1.2.4 Vestibular Migraine

Visually induced dizziness often occurs in vestibular migraine (Best et al., 2009; Chari et al., 2021; Dieterich et al., 2016; Formeister et al., 2018; Kim et al., 2023). Vestibular migraine is a type of migraine characterised by intense episodes of dizziness or vertigo, with or without a co-occurring headache. It affects around 2.7% of adults and is one of the most common forms of episodic dizziness (Formeister et al., 2018). The demographics of vestibular migraine in the population mirrors that of PPPD with roughly 2:1 female-to-male ratio and an average age of late-middle age (~53 years old (Formeister et al., 2018)). Visually induced dizziness is common in people with vestibular migraine both during attacks and interictally (Beh et al., 2019). A meta-analysis on vestibular migraine treatment found that pharmacological interventions and vestibular rehabilitation can be effective at lowering symptoms (Byun et al., 2021). For example, Aydin et al. (2020) compared vestibular rehabilitation to pharmacological treatment and a third group of both, finding when vestibular rehabilitation was included as treatment vertigo attack severity and duration decreased, compared to pharmacological treatment alone. The exercises in Aydin et al. (2020) utilised habituation and other forms of visual desensitisation and were performed in the home. Other research has also found that vestibular rehabilitation reduces the mean monthly migraine attacks and subjective dizziness intensity (Lee et al., 2015). Interestingly, Lee et al. (2015) utilised a rehabilitation paradigm first described in Chen et al. (2012), whereby participants were playing the Nintendo Wii (Jones & Thiruvathukal, 2012). Both Lee et al. (2015) and Chen et al. (2012) provide some evidence for the gamification of the rehabilitation of visually induced dizziness.

1.2.5 Ménière's Disease

Visually induced dizziness can be a symptom of those diagnosed with Ménière's disease (Best et al., 2009; Bruderer et al., 2017; Chari et al., 2021; Harcourt et al., 2014; Thomson, 2017). Ménière's disease is a disorder of the inner ear, which is caused by swelling of the membranous labyrinth (Harcourt et al., 2014). It has an estimated prevalence of 0.0019% in the USA and middle age onset (~40-to-60 years old, (Harris & Alexander, 2010)). Treatment for Ménière’s disease would typically be pharmacological with the potential for vestibular rehabilitation to stimulate peripheral vestibular compensation, and hearing aids used for any hearing loss (Harcourt et al., 2014). Visually induced dizziness often develops as a consequence of acute episodes of Ménière’s disease and following progressive damage to the labyrinth.

A more recent meta-analysis of vestibular rehabilitation as a treatment for Ménière’s disease was unable to conclude whether there was sufficient evidence of a positive effect of vestibular rehabilitation (van Esch et al., 2017). The inability to conclude a positive effect does not mean there is a negative effect of vestibular rehabilitation, with a more recent review finding improved quality of life in the short term, with a lack of long-term data to draw conclusions from (Rezaeian et al., 2023). Virtual reality based vestibular rehabilitation has had rehabilitative efficacy shown, with lower dizziness handicap inventory scores and lower reported dizziness after rehabilitation (Garcia et al., 2013). Aiming to treat visually induced dizziness for people with other diagnoses may inadvertently include treating people with visually induced dizziness that have Ménière’s Disease. Of the most common of these, there would either be a beneficial effect (vestibular neuritis, vestibular migraine) or potentially positive effect (Ménière’s disease), meaning that a visually induced dizziness focused vestibular rehabilitation approach would be beneficial to all.

1.2.6 Overview of Visual Desensitisation

This thesis focusses on visual desensitisation, which is a form of habituation, whereby presenting a stimulus to a participant will lead to an attenuated response in the future (Watts, 1971). Visual desensitisation involves showing complex visual patterns to participants to trigger their symptoms of visually induced dizziness, with the premise being that repeated exposure to these stimuli will eventually attenuate the symptoms of visually induced dizziness. For the purposes of the thesis, visual desensitisation rehabilitation refers to the above, whereas references to vestibular rehabilitation will mean physical exercises involving head and eye movements.

Pavlou et al. (2013) importantly demonstrated that visual desensitisation rehabilitation could be an effective rehabilitation approach for people with visually induced dizziness and can be achieved through the medium of a screen. In the study, participants were split into three conditions: all conditions received a DVD (digital video disc) containing optokinetic stimulation (multicoloured dots, vertical bars); one group had the DVD and were unsupervised; another received full field visual environment rotator, which projected stimuli such as dots or bars (see figures 4A or 4B for similar examples) onto walls and could alter the speed of these stimuli to vary stimulation; and the final group were given the DVD with weekly supervision from a clinician (Pavlou et al., 2013). Over 8 weeks, all groups showed significant improvement for vestibular and autonomic symptoms (heart pounding, excessive sweating, short of breath), meaning participants viewing the DVD showed similar symptom reduction to participants given full-field visual stimulation for rehabilitation (Pavlou et al., 2013). However, experiencing visually induced dizziness is unpleasant, and visual desensitisation aims to forcibly trigger these symptoms, which was likely a reason why the unsupervised DVD group had a 55% dropout rate, compared to 10% for the weekly supervised groups. This has been corroborated by other research, with many participants finding this type of rehabilitation unengaging (Gamble et al., 2023).

Micarelli et al. (2019) found that participants who did vestibular rehabilitation exercises and participants who did vestibular rehabilitation combined with visual desensitisation from a virtual reality headset both had lower symptom scores and higher quality of life scores; the latter combination group had significantly better scores for participants with mild cognitive decline. Micarelli et al. (2019) suggested this could be due to the nature of visual desensitisation rehabilitation provided through a virtual reality head mounted display: as long as the participants eyes' were open and looking at the stimuli, participants received the required visual stimulation. This evidence additionally reinforces other findings investigating rehabilitation for visually induced dizziness, namely that combining different approaches, such as visual desensitisation rehabilitation and vestibular rehabilitation exercises, is more effective than either in isolation (Law et al., 2024; Popkirov, Staab, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023).

Both Pavlou et al. (2013) and Micarelli et al. (2019) importantly demonstrate visual desensitisation rehabilitation can be achieved via electronic means and does not require physical stimuli to be effective. In sum, the evidence indicates that visual desensitisation rehabilitation can be done at home by a participant, but only if they can be motivated sufficiently (Pavlou et al., 2013).

1.2.7 How to Address Motivation

Within the past decade many avenues of health care have looked towards gamification as a means of increasing participant adherence to treatment. Gamification is where game design elements are applied in a non-game context, such as by utilising points, levels, and interactive targets / community goals (Patel et al., 2017). It is much more common to have gamification take the form of feedback or rewards for doing targeted behaviour, with a systematic review of gamification in healthcare finding that around 93% of included papers utilised these forms of gamification as of 2017 (Sardi et al., 2017). The idea behind gamification is that participants get rewarded for doing a desired behaviour. This reinforces good habits from participants and leads to better outcomes for participants utilising gamified healthcare compared to those that do not (Cafazzo et al., 2012). Gamification has more use than just healthcare and has also been successfully used in teaching and education. Notably, commercial success has been found for language learning applications, the most well-known being Duolingo (Duolingo, 2012; Vesselinov & Grego, 2012), with evidence that gamification increases adherence and motivation (Shortt et al., 2023; Wang, 2023). Increasing adherence and motivation whilst maintaining or surpassing health outcomes for alternatives makes for an ideal form of rehabilitation.

There are various ways to increase motivation. Self Determination Theory (SDT) posits motivation is a spectrum, from amotivation (no motivation) to external motivation (outside influence) and finally to internal motivation (entirely via self) (Gagné & Deci, 2005). From the Pavlou et al. (2013) study there is evidence participants will not self-motivation (55% dropout for non-supervised group) but will adhere to rehabilitation if supervised. This shows external motivation is sufficient for rehabilitation adherence. This ties in well with gamification, as gamification is almost entirely formed via external motivators (e.g. points or levels) (Sailer & Homner, 2020). A person will typically be motivated to play for gamified rewards as long as there are gamified rewards to attain (i.e. motivated). The issue with this is that endlessly adding new gamification requires resources. It, therefore, stands to reason that having participants be internally motivated is preferable, as such a participant would not drop out of rehabilitation.

Unfortunately, it can be difficult to shift a person from completing an activity due to external motivation to completing the activity due to internal motivation (Gagné & Deci, 2005). SDT demonstrates this can be done if three conditions are fulfilled: autonomy, competence, and relatedness (Gagné & Deci, 2005). Giving participants control of their own rehabilitation gives them autonomy. Providing feedback to participants on their ability can show them their competence. Connecting participants to each other and better letting them re-integrate into their pre-dizzy lifestyle can show relatedness. Importantly, evidence from Deci et al. (1994) show that internalisation happened when only two of these three factors were present. This means that even if not all participants respond to all three factors, they should still experience a shift from external to more internal motivation, achieving better rehabilitation outcomes.

1.2.8 Goal of this Thesis

Any new visual desensitisation rehabilitation would need to contend with motivation concerns from participants, as well as ensuring participants were doing the visual desensitisation rehabilitation correctly. This thesis deals with finding the minimum pathway to impact for a novel form of visual desensitisation rehabilitation that solves the issues of motivation and rehabilitation accuracy, whereby participants are unsure whether they are doing rehabilitation exercises correctly, noted above. Rehabilitation accuracy can be achieved via software, ensuring participants do not have the option of incorrectly completing their objectives, as shown in Pavlou et al. (2013), where participants had to passively view a DVD, and Micarelli et al. (2019), where participants had to passively view stimuli in virtual reality.

However, to better motivate participants, instead of passively viewing complex visual stimuli, participants can be an active part in their rehabilitation through gamification, where game design elements are applied in a non-game context, such as by utilising points, levels, and interactive targets / community goals (Patel et al., 2017). As such, this thesis details the development of a web-based gamified visual desensitisation rehabilitation tool called “Balance-Land”, which utilises visual desensitisation to treat the symptoms of visually induced dizziness. The 2nd chapter outlines our first prototype version of “Balance-Land”. Chapter 3 delves into the second iteration of “Balance-Land” and the iterative feedback we went through when talking to participants and clinicians. After three rounds of feedback, Chapter 4 presents the first large scale feasibility study to assess rehabilitation promise, usability, and engagement of Balance-Land. Chapter 5 extends the findings from chapter 4, analysing the gameplay data from the feasibility study in greater detail to determine whether any behaviour or play patterns of participants can explain the findings of the feasibility study. Chapter 6 analyses the exit interviews from the feasibility study, prioritises and implements key changes, and identifies other future directions for “Balance-Land”. Finally, Chapter 7 synthesises the findings from the preceding Chapters and provides guidelines for researchers and developments seeking to build gamified rehabilitation tools for visually induced dizziness or similar cohorts.

1.2.9 Triggers of Visually Induced Dizziness

As previously mentioned, visually induced dizziness is defined as being triggered by complex, large field, or moving stimulus (Bisdorff et al., 2015) and triggers can vary from person-to-person . Whilst it may seem paradoxical that symptom triggers of visually induced dizziness can be both consistent and vary person-to-person, there is an underlying explanation. Figure 1 shows common situations that can trigger symptoms of visually induced dizziness, with the consistent factors of provocation being: high contrast, high spatial frequency, visual-vestibular mismatch, repeating patterns, large field motion, along with luminance (Bisdorff et al., 2015). However, people with visually induced dizziness will typically be aware of potential triggers and take steps to mitigate them by utilising coping strategies. In the extreme, this has been noted as agoraphobia (Westphal, 1871) whereby the person would completely avoid the triggers rather than mitigating them. A less severe coping strategy would be, for example, wearing sunglasses to lower the perceived luminance, going shopping at irregular hours to lower the number of concurrent shoppers, or not purchasing furniture with high contrast repeating patterns.

Indeed, Moaty et al. (2017) had their participants start their vestibular rehabilitation with patterned wallpaper before moving onto more intense stimuli. If a person with visually induced dizziness has their symptoms triggered, they may have strategies to mitigate the symptoms and lower them to a manageable level, such as closing their eyes and sitting or lying down. There has also been some evidence that certain fragrances can lower symptom scores (Steenerson et al., 2022), although this may be due to making symptoms easier to endure, rather than a reduction of symptom levels.

The goal of mitigating behaviours is to lower the complexity of visual information being perceived, along with reducing any vestibular and visual mismatch. Finally, some people with visually induced dizziness will have less severe symptoms than others, which may end up being unpleasant but tolerable, as shown by Powell, Derry-Sumner, Rajenderkumar, et al. (2020) where the VVAS scores are distributed throughout the general population, some at clinically relevant levels. These people may be waiting for a vestibular diagnosis or have sufficient coping strategies that they do not require aid.

1.2.10 Measuring Visually Induced Dizziness

The Visual Vertigo Analogue Scale (VVAS) continues to be utilised to assess visually induced dizziness in many studies. The scale includes 9 questions about different scenarios a person may find themselves in which typically involve the aforementioned visual complexities such as: “walking through a supermarket aisle” or “being under fluorescent lights” (Dannenbaum et al., 2011). Participants are asked to mark on a blank number line bookended by 0 and 10 how much dizziness they would experience in the given situation, with 0 being no dizziness and 10 the most dizziness (see Appendix 1) (Dannenbaum et al., 2011). The participants are asked to not mark a line in a scenario in which they have not been in, resulting in a severity score calculated from only the items which were marked by the participant. After summation and scaling, there is a resultant score from 0 to 100 with a score of greater than 40 being considered severe (Frank et al., 2022).

A different measure has been developed to measure PPPD, called the Niigata PPPD Questionnaire (NPQ) (Yagi et al., 2019) which crucially asks about the postural and movement aspects of PPPD in addition to the visual aspects. There have been issues noted with the NPQ, notably that the questions do not factor onto their respective subscales, with visual factors accounting for 47% of the variance in the NPQ and the other two factors being categorised as active motion and mixed rather than movement and postural and one question not loading onto any factors (Yagi et al., 2021).

The final commonly used questionnaire to asses visually induced dizziness is the dizziness handicap inventory (DHI) containing 3 subscales: functional, emotional, and physical (Jacobson & Newman, 1990) and the dizziness handicap inventory is the most widely used self-report measure of dizziness (Mutlu & Serbetcioglu, 2013). The dizziness handicap inventory includes many non-visual questions, with research showing the questions load onto three factors: vestibular handicap, vestibular disability, and visuo-vestibular disability (Perez, 2001). More recent research has provided evidence that a vestibular subscale, which the researchers in the study created from a combination of questions from all 3 official subscales, can distinguish between people with compensated and uncompensated vestibular dysfunction (Zamyslowska-Szmytke et al., 2021). The dizziness handicap inventory has been critiqued for a lack of validity, with a meta-analysis finding a lack of content validity, inconsistent structural validity, and no smallest detectable change, resulting in a recommendation that only the total score be used (Koppelaar-van Eijsden et al., 2022). Nevertheless, the widespread use of the dizziness handicap inventory makes comparison between studies and participants easier, even if there are issues with the measure itself.

1.2.11 Why Measure Visually Induced Dizziness

PPPD is the most common diagnosis in tertiary balance clinics and is a functional disorder (Bisdorff et al., 2015; Staab et al., 2017); there is no test that can be given and no imaging that can be done to accurately classify someone as having PPPD. There have been a number of posturography and balance related tests that can be given: the rod and frame test (Witkin & Asch, 1948); a functional gait test (Barnes & Crutchfield, 1990); or computerised dynamic posturography (Lipp & Longridge, 1994) (non-exhaustive list); and people with visually induced dizziness have a higher postural and head sway along with requiring more visual refixations during busy visual environments (Chaudhary et al., 2022). Whilst some people with PPPD may score abnormal test results in some of these, they will not score abnormal results in all of them, and some people PPPD will get scores within the range of the general population (Powell, Derry-Sumner, Rajenderkumar, et al., 2020). This is because these tests are aiming to measure different aspects of visual and vestibular function, such as the visual vertical perception: they do not measure PPPD.

Self-report measures will aim to measure visually induced dizziness, since it is measurable, as a proxy, instead of PPPD, which is not currently directly measurable. However, an issue with measuring visually induced dizziness is that it is not condition specific and can occur in a variety of conditions. This necessitates a view of visually induced dizziness that goes across conditions. For example, Ménière's Disease is currently not curable (Liu et al., 2020) but research has shown that vestibular rehabilitation often leads to a reduction in visually induced dizziness symptoms and improvements in quality of life (Rezaeian et al., 2023). The best way to assess the reduction in visually induced dizziness symptoms would, therefore, be to utilise a measure of visually induced dizziness.

1.2.12 Theories of Visually Induced Dizziness

Humans use three main senses in order to maintain balance and posture (Kell & van Duursen, 2005), see figure 2. The first and most reliable is the inner ear and vestibular system. The other two are the visual system and the proprioceptive feedback from the body. The typical pipeline for developing visually induced dizziness is thought to follow the following pattern: an acute vestibular insult occurs in a human; they are no longer able to rely on their most reliable balance system (vestibular), and must instead rely on the visual and proprioceptive systems (see Figure 3) (Staab, 2012). The person must now develop novel strategies for maintaining balance and posture in the absence of reliable vestibular information. Eventually, the vestibular insult may heal or be compensated for with recalibration. Crucially, the person does not stop using their adaptive balance and postural strategies. The strategies now are harming the person and have become maladaptive. The person now has visually induced dizziness, and after visiting with a specialist clinician multiple times they may gain a diagnosis, most commonly PPPD (Staab et al., 2017).

The most prominent theory of visually induced dizziness, which attempts to explain the above, is called visual dependence. Visual dependence is defined as the "reduced ability to disregard visual cues in complex or conflicting visual environments" (Maire et al., 2017). When the vestibular system and the visual system come into conflict, the resultant incongruence is the feeling of visually induced dizziness. This feeling becomes stronger when the mismatch between the senses becomes more apparent, such as in visually complex environments, or those with high visual flow. The theory of visual dependence, essentially, then becomes an issue of the body having issues with weighting reliable information.

It is logical, then, that a solution would be to reweight the information the body is utilising, which is currently a viable rehabilitation strategy: habituation (Axer et al., 2020; Pavlou et al., 2013; Popkirov, Stone, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023), although there is no standardised rehabilitation technique for visual dependence (Maire et al., 2017). As mentioned in prior sections, purely visual forms of habituation have been referred to as “visual desensitisation” (Staab, 2023; Trinidade, Cabreira, Kaski, et al., 2023), which will be explored more thoroughly later.

This means there is a diagnosis with clearly defined criteria, a theory for the diagnosis, and a rehabilitation that works. There is only one issue: the theory of visual dependence does not account for all that is found in visually induced dizziness. The necessity of an original peripheral vestibular insult can be questioned. There are many reports of people suffering visually induced dizziness after head injury (Misale et al., 2021) as well as through migraine and psychiatric conditions, such as anxiety (Maire et al., 2017). Around 15% of people with PPPD have an initial psychogenic illness, either anxiety or panic attacks, rather than an acute vestibular insult (Staab et al., 2017). These people would have no issue with their peripheral vestibular system prior to developing PPPD and visually induced dizziness. This makes it less clear as to why these 15% of people would start relying on their vision more than their vestibular system for balance.

An alternative viewpoint would be that it is not dependence on vision that matters per se, but a propensity for a person to visual overload (see section below) – which then becomes exacerbated when vision needs to be more relied upon. It may also be exacerbated by anxiety and trauma, which could explain why many clinicians report that anxiety needs to be treated first or concurrently in order for rehabilitation to be successful (Popkirov, Staab, et al., 2018; Staab et al., 2017).

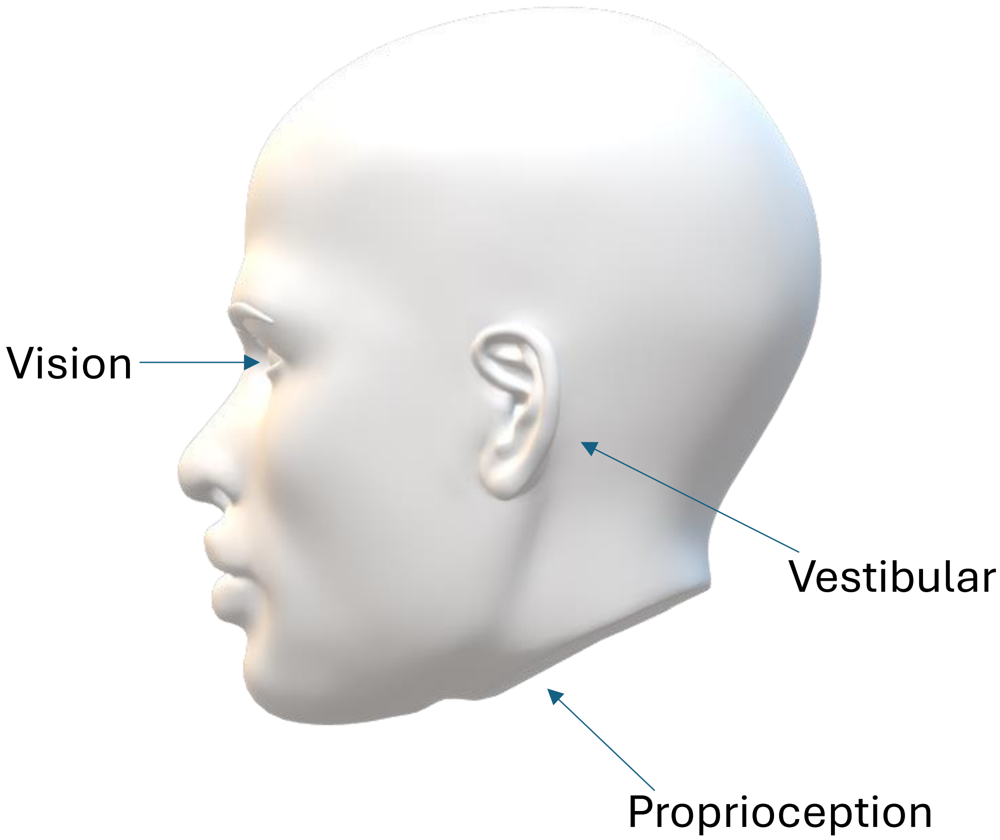


Figure 2, the three primary mechanisms for determining balance.

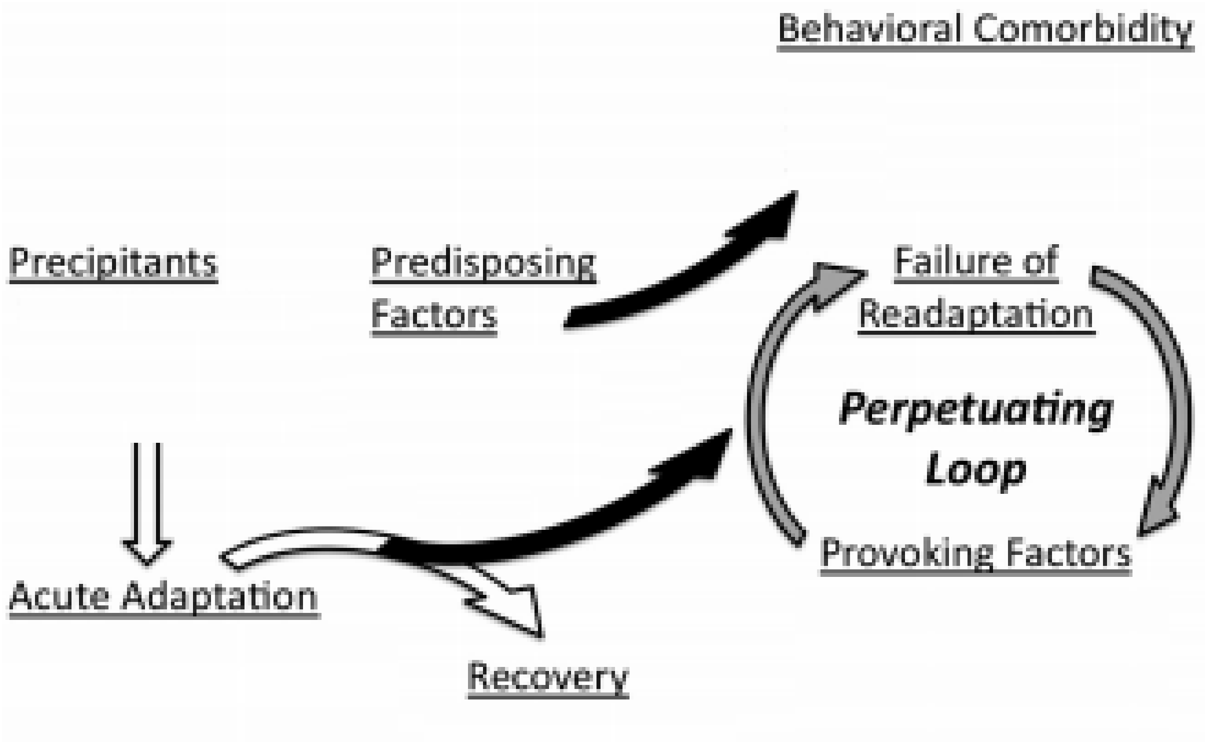


Figure 3, Example picture of maladaptive loop from Staab (2012).

1.2.13 Anxiety in Visually Induced Dizziness

Anxiety has increasingly been recognised as an important factor in visually induced dizziness and associated conditions, with 12% of people in dizziness clinics meeting a criteria for an anxiety disorder (Murphy et al., 2021; Staibano et al., 2019). People with visually induced anxiety often develop intense phobias and avoidance of the situations that trigger their dizziness, which is understandable given the intense symptoms they experience (see above section on history of visually induced dizziness). Additionally, or alternatively, people with PPPD will quite often have hyper vigilance around trip hazards and threat perception to their balance, and sometimes even to their gait: going so much as to develop a gait disorder due to their hypervigilance (Bisdorff et al., 2015).

Recent work has discovered that early anxiety predicts the development of PPPD and thus visually induced dizziness (Trinidade, Cabreira, Kaski, et al., 2023). Anxiety as a predictor of PPPD following a vestibular event supports anxiety playing a crucial role, however the evidence showed that anxiety was related to high body vigilance. Specifically, conscious attention to dizziness, and catastrophic worries about vestibular symptoms, were the most important aspects of anxiety, rather than generalised anxiety (Trinidade, Cabreira, Kaski, et al., 2023).

Overall, then, anxiety is an important component of the development and maintenance of visually induced dizziness in PPPD, of quality of life in PPPD, and perhaps in other conditions as well. Therefore, any rehabilitation option should also aim to target a reduction in anxiety alongside vestibular symptoms (rehabilitation is discussed below).

1.2.14 Visual Sensitivity

It has been noted that different people with visually induced dizziness may be triggered by different stimuli, or even be differentially triggered by the same stimuli, with findings indicating a hypersensitivity to moving or conflicting visual stimulations in those with visual dependence (Maire et al., 2017). One explanation for this has been possible coping strategies, but another could be due to the level of sensitivity of each person. As one may expect, each person will vary in their response to external stimuli. This can range from being unaware of the luminance difference between two lights, that is, a luminance change below your just noticeable difference (Stern & Johnson, 2010). This is a kind of sensory sensitivity called a threshold sensitivity measurement.

Another kind of sensitivity would be avoiding certain areas due to the lighting, such as artificial lighting found in a supermarket. This is known as subjective sensory sensitivity. It is this latter kind of sensitivity that is most relevant and interesting to visually induced dizziness. This is because the former kind, threshold sensitivity, has had mixed findings in relation to visually induced dizziness (Chaudhary et al., 2022; Powell, Derry-Sumner, Shelton, et al., 2020; Wurthmann et al., 2021). However, subjective sensitivity is defined by how a person would respond to a stimulus (Fischhoff et al., 1979). As an example, one person may wear a hat or sunglasses to lower the brightness on a sunny day, whereas someone that does not perceive the day as being too bright would not, as described by a person with PPPD:

"I used to wear sunglasses all the time because I really needed to tone down the world. It was like it was too like, too contrast, and visual! And it would like throw me." Lara: 567-568 (Gamble, 2022)

Knowing how a person would react to a given set of stimuli is much more useful for rehabilitation and recent work has gone into trying to measure this type of visual sensitivity (Price, 2023). It is thought that these subjective sensitivities are linked to neural activations, such that the people who are reporting subjective differences due to a sensory input would also, at the same time, be experiencing large neural activation in the sensory regions (Edden et al., 2009; Salinas & Sejnowski, 2001).

Sensory sensitivity is relevant to visually induced dizziness because some studies have found that people that have symptoms of visually induced dizziness have reported increased visual sensitivity and visual stress, particularly to environments that deviate from the statistical properties of natural scenes (Lukacova et al., 2023; Pavlou et al., 2006; Powell et al., 2022). Natural environments, which humans have evolved to thrive in, have classic spectral properties with a predominance of low spatial frequencies and a wide range of orientations (Kaping et al., 2007) . This contrasts with many modern environments (e.g. a supermarket), which are characterised by more high spatial frequencies and a limited range of orientations. Powell et al., (2022) suggested that people with visually induced dizziness had a predisposition for sensory overload in these environments, characterised by an increase in visual discomfort and visual over-activity. This then contributed to the visually triggered dizziness when the people with this predisposition developed a peripheral vestibular insult or other triggering event. More recent work by Price (2023) found that visual sensitivity factorised four ways: strobing, pattern, intense visual environment, and brightness, all areas people with visually induced dizziness can struggle with, potentially explaining the differential effect of stimuli. These differences in spatial properties seem to be noticed by the brain and result in neural activity, which may be why people with visually induced dizziness have more difficulty in artificial scenes (Ward, 2019).

1.2.15 Sensory Overload

Not only can some people be more sensory sensitive than others, but some people can experience “sensory overload”. A recent concept analysis of the literature found the defining attributes of sensory overload as: perceptual distortions; sensory stimuli above desired or usual level; continuous unchanging or intense stimuli (Scheydt et al., 2017). Per these defining attributes, visually induced dizziness and

PPPD can be thought of as a form of sensory overload, as visually induced dizziness includes all three defining attributes (Staab et al., 2017) and mentioned by Regina in Gamble (2022). Sensory overload can be readily seen as a consequence of unmanaged behavioural sensory sensitivity, whereupon a person not utilising a coping strategy to reduce the perceived stimulation to a manageable level would then be exposed to a continuous and intense stimulus, such as Lara (quoted above) not utilising their sunglasses to lower the brightness to a manageable level, and Regina below:

"Its cause, it's almost like a sensory overload. So, if you cut off one of the senses it sort of helps you deal with it a bit better" (Regina: 288-290, (Gamble, 2022))

Doucé and Adams (2020) found they could induce sensory overload in otherwise healthy participants shopping in a simulated grocery store by utilising high arousal light, music, and scent. It would be unsurprising if a person were to avoid a situation that may cause sensory overload if they were unable to sufficiently mitigate the incoming sensations, with evidence showing increased use of sensory avoidant behaviour for people with visually induced dizziness (Powell, Derry-Sumner, Shelton, et al., 2020). We also know that anxiety is an important component of visually induced dizziness (Staab et al., 2017) and that a person with anxiety will have maladaptive avoidant behaviours to perceived threats (Arnaudova et al., 2017). Taken together, people that experience sensory overload will endeavour to either lower their incoming sensations to avoid overload, or, if unable to accomplish that, instead entirely avoid the situation that may cause sensory overload, which mirrors behaviour exhibited by people with visually induced dizziness.

1.2.16 Rehabilitation of Visually Induced Dizziness

In a review of PPPD treatment, Popkirov, Stone, et al. (2018) found there to be three ways to rehabilitate effectively: vestibular rehabilitation; cognitive behavioural therapy; and pharmacological intervention (mainly selective serotonin reuptake inhibitors, SSRIs). Vestibular rehabilitation came in the form of providing complex patterns and visual flow through at-home exercises that were demonstrated in-lab or via video (see (Burzynski et al., 2017)). These forms of rehabilitation exercises work to isolate the visual, vestibular, and proprioceptive senses, typically by having initial exercises be performed in a supine position with minimal distractions (a blank wall or ceiling). This allows for any visually induced dizziness experienced to be as a result of visual and vestibular conflict, as the proprioceptive feedback should be negligible.

Additional vestibular and proprioceptive feedback can be introduced by moving from a supine, to a seated, a standing, and eventually a moving position. Stimulation can be minimal, such as using a finger for visual stimulation, to quite complex, such as printing off high contrast visual gratings to view. Whilst it is true that habituation as a form of vestibular rehabilitation may lower symptoms, it then follows that any form of rehabilitation focused on reweighting the visual vestibular information should work. Cognitive behavioural therapy focused on dizziness (not depression or anxiety) has recently given promising data on rehabilitating PPPD and visually induced dizziness (Herdman et al., 2022). The goal of this cognitive behavioural therapy was to focus on normalising any maladaptive postural strategies they had developed, along with habituation, and out-performed the gold-standard vestibular rehabilitation arm of the trial.

Vestibular rehabilitation has been shown to be able to improve function and decrease dizziness symptoms (Whitney & Sparto, 2011). Vestibular rehabilitation can give symptom relief without side effects, reducing symptoms and improving quality of life (Nada et al., 2019) and can be affected by a number of physical factors, such as age, physical activity, length of symptoms, comorbidities, sleep, and medication. Psychological factors that affect vestibular rehabilitation are anxiety, depression, fear of movement, and fear of falling (Whitney et al., 2020). Those who do not benefit from vestibular rehabilitation had been diagnosed longer, had more severe symptom scores, utilised more composite rehabilitation exercises, and had more complex aggravating factors (Nada et al., 2019). Loss of balance leading to falls is linked to dizziness, with vestibular disorders all showing improvement as a result of vestibular rehabilitation exercises, such as a vestibular-ocular-reflex exercises involving focusing on a point whilst moving the head in one axis of motion e.g. yaw (Alrwaily & Whitney, 2011). However, customised rehabilitation has a better effect than generic rehabilitation, with the vestibular therapist providing regular feedback to the participant on proper form (Alrwaily & Whitney, 2011).

Participants express concerns over how vestibular rehabilitation can change their symptoms and potentially restrict their lifestyle (Morris et al., 2008). Moaty et al. (2017) utilised the incremental rehabilitation technique in their study by having participants start off with physical stimuli before moving onto head-mounted displays, which were more stimulating. People have had issues with this form of physical vestibular rehabilitation (Burzynski et al., 2017), namely falling into three categories: anxiety around the person being unsure if they are doing the exercises correctly; the person not knowing whether they should be progressing to different exercises; and people getting bored or fatigued from doing the rehabilitation and not maintaining to their rehabilitation schedule. Pavlou et al. (2013) importantly demonstrated that rehabilitation need not occur with only physical stimuli, but virtual ones can also provide an equal benefit to rehabilitation.

As mentioned in the above anxiety section, anxiety rehabilitation should be done in tandem with visually induced dizziness symptom reduction. Anxiety can lead to maladaptive strategies that, in turn, result in new disorders, such as a gait disorder in a person with PPPD (Bisdorff et al., 2015) or agoraphobia (Cordes, 1872; Westphal, 1871). This means that treating anxiety can result in fewer maladaptive behaviours, which will then lead to fewer symptoms being experienced. Anxiety relating to the self and the effects of vestibular symptoms, together, provide a compelling explanation for the findings of Herdman et al. (2022): the cognitive behavioural therapy focused on the physical aspect of the anxieties, lessening the maladaptive behaviours.

Another way that treating anxiety could work is through habituation. Essentially, removing or lowering the anxiety people have about certain environments that trigger their symptoms , such as agoraphobia (Cordes, 1872; Westphal, 1871), could lead to a person experiencing those environments more often. If a person with visually induced dizziness spends more time in triggering environments more often, then they will passively habituate themselves more (Holmberg, 2020). This is because the real world is much more complex than any of the visual stimuli that are utilised in visual desensitisation rehabilitation or vestibular rehabilitation, providing a more effective rehabilitation tool. Either of these two anxiety pathways can be integrated into the theory of visual dependence to explain why specifically targeting anxiety has a knock-on effect of reducing visually induced dizziness symptoms.

1.2.17 Visual Desensitisation

Vestibular rehabilitation for visually induced dizziness often takes the form of visual desensitisation (Alrwaily & Whitney, 2011), which has been referred to as visual desensitisation rehabilitation through the thesis. This form of stimulation has long been studied, starting with researchers looking at the optokinetic reflex, also known as the optokinetic nystagmus, and aiming to quantify parameters on whether humans have a similar reaction to animals (see Figure 4C) (Tijssen et al., 1989; Zee et al., 1976), finding that the optokinetic reflex can be accurately measured and can vary between participants. From this, investigation turned into whether optokinetic stimulation could be utilised when treating vestibular deficits, finding that optokinetic stimulation could reduce unsteadiness in elderly patients (Semont et al., 1992). Further study revealed participants with bilateral and unilateral labyrinthine defects, with the labyrinthine being thought necessary for normal optokinetic reflex response in humans (Zee et al., 1976), had their body stabilisation as measured by dynamic posturography recorded at levels similar to matched healthy controls (Vitte et al., 1994). The number of training sessions in Vitte et al. (1994) to achieve normal sway results was 8, comprised of sessions 15 minutes or less, utilising rotating dots in a stationary room (see Figure 4A). The crucial development here that made the rehabilitation a form of visual desensitisation rehabilitation was that the rehabilitation only ever stimulated the visual system, aiming to keep vestibular and proprioceptive inputs minimal.

Pavlou et al. (2004) investigated whether visual desensitisation rehabilitation could succeed by taking participants with peripheral vestibular deficits and crucially had prior experience with vestibular rehabilitation with no or partial improvement. These participants were given either a customised exercise regime or optokinetic stimulation (see Figure 4B), with both groups showing significant improvements to posturography scores (Pavlou et al., 2004). However, the group treated with the optokinetic stimulation had significantly greater improvements for their visual vertigo symptom scores, with anxiety and depression decreases significantly correlating with visual vertigo symptom score decreases (Pavlou et al., 2004). Although, it must be said that later research did not find a link between posturography results and visual vertigo symptom scores, indicating re-weighting of sensory information in participants with high scores (Pavlou et al., 2006). Unfortunately, Vitte et al. (1994)

did not include a separate measure of visual vertigo, which is perhaps unsurprising as visual vertigo was largely introduced by Bronstein (1995) a year after the research was published. Fortunately, Pavlou et al. (2004) did include a separate measure for visual vertigo symptoms, which reinforces the findings of Vitte et al. (1994).

With the use of optokinetic stimulation being a valid form of rehabilitation for visual vertigo, research went into the different ways this could then be applied to participants. Pavlou et al. (2013) importantly demonstrated that habituation need not occur with only physical stimuli, but virtual ones can also provide an equal benefit to rehabilitation, in this case a DVD of optokinetic stimulation. Participants that were given a DVD of optokinetic stimulation had comparable rehabilitation results to those given traditional full-field visual stimulation (Pavlou et al., 2013). Unfortunately, Pavlou et al. (2013) also found that participants given a DVD and left to their own devices struggled with adherence to the rehabilitation schedule, with 55% dropping out, which was higher than other forms of rehabilitation. Nevertheless, strong evidence that optokinetic stimulation via electronic screen was a viable treatment pathway for visually induced dizziness helped virtual reality as a rehabilitation modality become more popular.

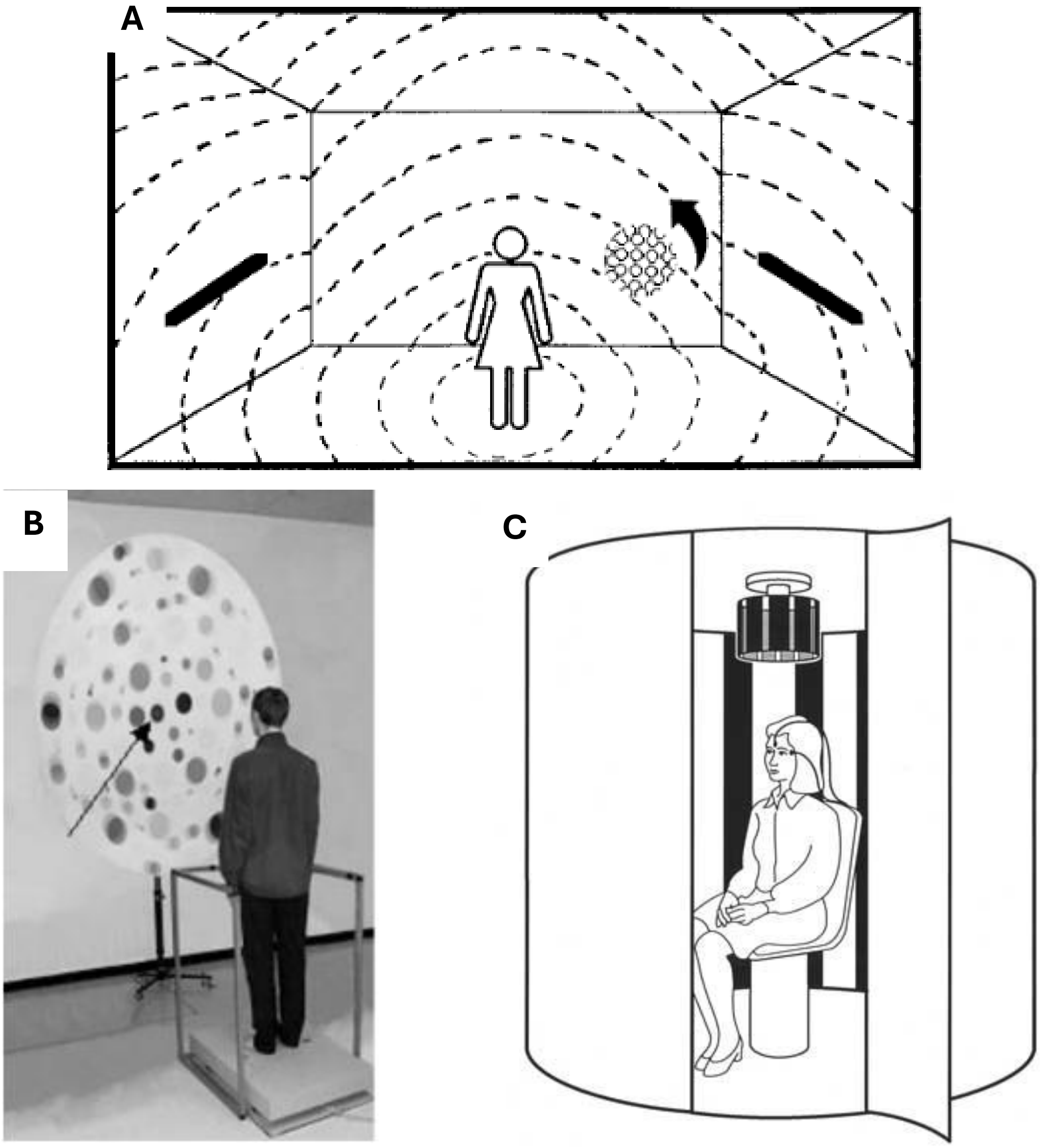


Figure 4, Optokinetic stimulation as rotating dots as used in Vitte et al. (1994, top) and a rotating disc as used in Pavlou et al. (2004, bottom left). A person in an optokinetic drum is shown in the bottom right, similar to stimuli used for evoking the optokinetic nystagmus.

1.2.18 Virtual Environments and Virtual Reality

There have been many studies exploring virtual reality or electronic forms of rehabilitation for visually induced dizziness since Pavlou et al. (2013). Alahmari et al. (2013) did not use virtual reality headsets, instead having participants walk on a treadmill surrounded by screens that showed a virtual grocery store. There were significant improvements for this virtual group and the traditional vestibular rehabilitation control in self-report and balance measures, with no differences between groups (Alahmari et al., 2013). Importantly, Alahmari et al. (2013) found the participants in the virtual reality group had worse symptoms during the rehabilitation, yet still had an overall symptom reduction, implying that this rehabilitation may work with a different mechanism when compared to traditional vestibular rehabilitation.

Garcia et al. (2013) found that participants with Ménière’s Disease had greatly reduced dizziness handicap inventory scores along with lower dizziness analogue scores after rehabilitation with virtual reality, showing virtual reality rehabilitation works for visually induced dizziness rather than a specific diagnosis. Meldrum et al. (2015) compared virtual reality to exercise-based vestibular rehabilitation and found significant improvements on all outcome measures for both groups with no significant differences between groups. However, the virtual reality group reported more enjoyment, less difficulty with the rehabilitation, and less tiredness after balance exercises (Meldrum et al., 2015), showing virtual reality as a modality could afford similar rehabilitative benefit but better quality-of-life during rehabilitation.

Fransson et al. (2019) only investigated healthy controls, having them view a simulated rollercoaster repeatedly for 90 seconds. Compared to their first session, repeated exposure resulted in reduced postural instability, indicating successful sensory re-weighting occurred, providing strong evidence that virtual reality can be effectively utilised for visual desensitisation (Fransson et al., 2019). Gallagher et al. (2020) aimed to investigate the mechanisms by which virtual reality works, investigating whether vestibular perceptual sensitivity was affected by virtual reality exposure. This was true: sensitivity to vestibular signals was greatly diminished during virtual reality, but only when visual and vestibular cues conveyed information for the same plane of self-motion (Gallagher et al., 2020).

A comprehensive review of virtual reality rehabilitation paradigms by Bergeron et al. (2015) reveal an overall positive effect of virtual reality rehabilitation, suggesting a minimum of 150 minutes of cumulative exposure recommended to ensure a positive participant outcome. Mandour et al. (2021) found no difference in rehabilitation outcomes for participants with visual vertigo when comparing optokinetic stimulation to virtual reality rehabilitation with home-based exercises. This finding extends work by Pavlou et al. (2013), showing electronic stimulation does not necessarily need to be optokinetic patterns in nature to establish beneficial rehabilitation results.

However, participants have found optokinetic stimulation unengaging (55% dropout (Pavlou et al., 2013)) and experience cyber-sickness in virtual reality (Bergeron et al., 2015), meaning people with severe vestibular symptoms can be unsuited to virtual reality rehabilitation. This is consistent with SDT, as participants were given little autonomy, little training (lack of competence), and the relatedness offered was unclear.

Virtual reality has the upside of completely capturing the visual field due to how the headset encompasses the head and provides a complete mismatch between the visual and vestibular inputs, theoretically providing the best way to habituate via reweighting cues. The major issue with utilising virtual reality headsets, apart from their cost, is that people with visually induced dizziness experience severe symptoms when using them (Kim et al., 2018), making the people immediately want to stop using them. This goes against good practice for habituation, which aims to gradually increase exposure so as to not traumatise people going through the rehabilitation (Gans, 2015). This means virtual reality vestibular rehabilitation can only work for people with lower symptom levels, or people who are further along their rehabilitation journey. Indeed, many traditional vestibular rehabilitation programmes will gradually increase intensity to avoid overloading the participant, such as Moaty et al. (2017) who started off with physical stimuli before progressing participants to DVDs with optokinetic stimulation.

As mentioned in the anxiety section, it is unclear as to the exact mechanism that cognitive behavioural therapy rehabilitates visually induced dizziness: directly or indirectly. Directly, being anxiety is causing excessive focus on posture and threat perception, with a reduction leading to lower symptoms, and indirectly via lower anxiety leading to increased habituation using real-world environments. It is likely that SSRIs operate in a similar manner to anxiety reduction, through either a direct or indirect pathway, with them being used to treat anxiety (Popkirov, Stone, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023). Vestibular rehabilitation to reduce visually induced dizziness symptoms in environments has a knock-on effect of allowing participants to better experience those environments, potentially reducing anxiety. One issue with reducing symptoms but not targeting anxiety is that the person may not be aware their visually induced dizziness symptoms have reduced, and the anxiety itself is so strong it is holding them back from living their life, making any rehabilitation of PPPD and visually induced dizziness having an anxiety effect a requirement.

1.3 Gamification

1.3.1 What is Gamification?

Gamification is where game design elements are applied in a non-game context to motivate and enhance user engagement (Patel et al., 2017). This can be achieved by leveraging features commonly found in games such as points, levels, and interactive targets / community goals. It is much more common to have gamification take the form of feedback or rewards for doing targeted behaviour, with a systematic review of gamification in e-health finding around 93% of investigated papers doing this as of 2017 (Sardi et al., 2017). Other ways of incentivizing people to behave in a certain manner were: a progress bar; social connection/ peer pressure; or a challenge or “quest” to complete a certain activity (Sardi et al., 2017). For example, one such study had a goal of motivating participants to step more each day as an indicator of cardiovascular health (Patel et al., 2017). To achieve gamification they recruited families, and each family would work as a team to keep their points and go up ranks from bronze to platinum. The research team utilised: loss aversion, by failure to reaching step goals reducing points; a random family member being picked for the day to represent the family resulting in variable reward; and lifelines for each person in the event they were sick, or unable to complete their goals for some reason, and provide leniency (Patel et al., 2017).

Other forms of gamification can come by getting people to play actual games made on dedicated game systems such as the Nintendo Wii (Jones & Thiruvathukal, 2012) or virtual reality instead of gamifying the real world. Popular modalities for this would be the Xbox Kinect (Kamel Boulos, 2012) or the Nintendo Wii (Jones & Thiruvathukal, 2012), whereby the game can detect physical movement inputs. By assigning the patient to play a game where the movements they need to rehabilitate are the same movements they game requires for a high score, they should get better over time (Alfieri et al., 2022). This leaves a plethora of options to choose from when utilising gamification, but it is not always clear how much, if any, gamification should be implemented.

When defining gamification, it must be included in defining what gamification is not. Some studies have utilised virtual reality when looking at visually induced dizziness, e.g. Riccelli et al. (2017), but virtual reality is a modality for rehabilitation and not an end-goal or a form of gamification in and of itself. Exploring Riccelli et al. (2017) further, the study involved participants passively viewing a rollercoaster video whilst wearing a virtual reality headset. There were no game elements in the study and the participants were not required to make any decisions. Conversely, Lee et al. (2015) utilised the Wii as a modality for some exercises, but crucially also got participants to play Wii games for some of their rehabilitation. Gamification requires these game elements, which is why Mandour et al. (2021) found no difference between their virtual reality arm and traditional vestibular rehabilitation arm: they were essentially doing the same rehabilitation. More broadly, Xie et al. (2021) did a systematic review which finds mixed benefits of virtual reality as a modality.

1.3.2 Advantages of Gamification

As previously mentioned, increasing motivation is one of the primary goals and can be achieved through providing more autonomy, increasing participant's competence, and offering relatedness to others. Gamification for motivation can come in many forms, from serious games similar to World of Warcraft (Entertainment, 2004), to mobile games that track steps and encourage attaining goals, such as Duolingo (Duolingo, 2012). Gamification has been investigated in healthcare extensively for: cancer, nutrition, fitness, pain assessment, arthritis, cerebral palsy, and even hygiene. The gamification approaches to all these healthcare areas, however, were not identical and some may be more suited to visually induced dizziness rehabilitation than others.

Schönauer et al. (2011) utilised full-body motion capture with the Kinect (Kamel Boulos, 2012) to help manage chronic pain rehabilitation, with the goals of physical reconditioning and improving reach. A customised story narrative was created that participants viewed positively, and played via motion capture suit and a treadmill, which unfortunately poses some difficulty for home rehabilitation (Schönauer et al., 2011). Participants rated the games as usable, enjoyable, and preliminary data showed a decrease in pain scores (Schönauer et al., 2011). It is unsurprising Schönauer et al. (2011) found success with their gamification options: the Kinect is intuitive to use, allowing feelings of competency; participants could choose to go at their own pace, fulfilling needs of autonomy; and the Kinect is linked to a person's Xbox account, allowing participants to connect with others, although this was not utilised in the study. An alternative way of gamifying via a mobile phone app targeted vegetable consumption in children, finding parents liked the game (Beltran et al., 2012). However, Beltran et al. (2012) received feedback that many participants just ignored any instructions and had difficulty with the controls, highlighting how even motivated participants can struggle with a supposedly simple user interface. The user interface impacted the participants' feelings of competency. The children are the end user of the gamified app; however, the parents are the people who decide whether their child will use the app, removing any autonomy from the child. As noted by Deci et al. (1994), missing at least two of the motivational pillars imply longer-term use of the app would not positively affect motivation, unless via constant external motivation through the parent.

Allam et al. (2015) utilised points and medals in a web-based intervention on rheumatoid arthritis, finding them effective motivators for getting participants to engage with their intervention. Stinson et al. (2013) developed a phone application for pain assessment for adolescents with cancer. Pain can be a clinically relevant indicator for people with cancer, and the adolescents were encouraged to rate their pain consistently with rewards structed around ranking up with badges, streaks, and video affirmation (Stinson et al., 2013). The motivators were a success, with 81% of participants having 100% compliance (Stinson et al., 2013). Points, medals, badges, and streaks are effective forms of gamification as they immediately provide feedback and feelings of competency to participants, ensuring they are rewarded for a good job. Likewise, they can be easily communicated to others to allow for relatedness. Video affirmations are likely to result in even more feelings of competency in participants, although their relation to autonomy and relatedness is not as strong.

Michmizos et al. (2015) investigated gamifying ankle rehabilitation for children with cerebral palsy, finding improvements in explicit and implicit motor learning. All 3 optional games focused on use of the ankle for successful completion (e.g. football) and were modified based on performance, ensuring no game was too difficult

(Michmizos et al., 2015). The positive findings from Michmizos et al. (2015) are consistent with SDT, as the children were all likely wanting to play football, targeting autonomy. Dynamic difficulty adjustment ensures all the participants feel competent, and any skills learnt can be used to play actual football with friends, for relatedness.

Gamification has even been utilised for type one diabetics to aid with blood-glucose monitoring measurements (Cafazzo et al., 2012). Cafazzo et al. (2012) motivated participants with iTunes music rewards and encouraged speculation as to why the participants' blood-glucose measurement was the way it was, with the aim of leading to better understanding of their blood-glucose management. The external rewards, in the form of iTunes, aimed to keep the participants motivated long enough until their understanding of why their blood glucose was changing as a result of their behaviours, leading to an internal shift in motivation.

Whilst all of the above research found respective benefits for their area of investigation, the methods employed in gamification studies extend further: some had abstract goals, such as a mobile fitness application (Keung et al., 2013), or mental health (Craven et al., 2014; Dennis & O'Toole, 2014; Miloff et al., 2015) which looked at applications for trait anxiety, social anxiety, and for attention deficit hyperactive disorder (ADHD), respectively.

Gamification is a tool for engagement and motivation and thus has not only been used in healthcare, but also for teaching. An overview by Sailer and Homner (2020) found many similar successes of gamification in a teaching context, with common mobile phone applications being gamified for this purpose, such as Duolingo (Shortt et al., 2023). Duolingo goes for a heavy-handed gamified approach, with virtual rewards (points, daily streaks) and social competition (leagues, comparison to phone contacts) to motivate engagement and teach languages to users (Wang, 2023). This makes sense, as one of the healthcare applications of gamification was partially an issue of patient education, e.g. Beltran et al. (2012) or Borghese et al. (2013), meaning extending patient education to academic education was a small leap.

As previously mentioned, there are many choices on how to gamify something, from constant measurement, feedback, progress reports, virtual rewards, to social comparison (non-exhaustive). Research has found they can be as effective as each other and it depends on the person and activity in question, e.g. promoting physical activity (Zuckerman & Gal-Oz, 2014). Many of the successful (i.e., motivated) attempts at gamification examined in this section align with SDT (Gagné & Deci, 2005), providing participants autonomy and competence, and occasionally relatedness. In some cases, such as Cafazzo et al. (2012), the evidence supports external motivation being used as a starter point to shift participant motivations to a more internal and autonomous end-state, which would be ideal for Balance-Land.

1.3.3 Barriers of Gamification

Gamification does come with barriers, though. The primary barrier is the technological literacy required to play a game. For example, the currently most played game on steam is counter- strike two (Steam, 2024)(see Figure 5). The basic controls of the game will require a person to move the camera with the mouse in the right hand and move the character's body with the left hand, meaning each hand controls an independent axis of movement (see Figure 6) and has an entirely more complex economy that must be understood, as explained in Jordan (2020). Whilst a first or third-person shooter design can be arbitrary for games, a third-person perspective for vestibular rehabilitation would give a central character fixation point. This would be useful for simulating some of the simple forms of vestibular rehabilitation (Alrwaily & Whitney, 2011; Whitney & Sparto, 2011), it could provide an impediment when full-screen flow is required. Most games or game arch-types have similar control schemes, such as most free-move and free-look games mimicking the WASD keys for movement and the mouse for camera control (Gkikas, 2007), or the use of a controller (see (Cummings, 2007)). As seen from Figure 6, there are numerous controls beyond the basics of movement, all of which will be required to fully play the game.

For a person that has never played games before, learning all the controls is a difficult task and rehabilitation could not begin until training through these controls is complete. As found by Pavlou et al. (2013) and predicted in SDT by Gagné and Deci (2005), passively forcing a participant to view complex visuals leads to less internal motivation. Autonomy is a crucial aspect that must be maintained for motivation (Gagné & Deci, 2005), which can be achieved through allowing the participant to choose their visual environment. Unfortunately, not all aspects of a commercial game will be designed with visually induced dizziness rehabilitation in mind, resulting in some exploration choices by a patient leading to little or no rehabilitative benefit. However, creating a custom virtual world with visually induced dizziness rehabilitation as the goal would allow for a simplified control scheme and any exploration choice the patient makes would have a positive rehabilitative benefit, whilst still preserving autonomy. As a consequence of aiming to enhance motivation in this manner, there is the drawback of enforcing a minimum level of computer literacy on the participant, to ensure they can navigate the virtual environment sufficiently well for rehabilitation.

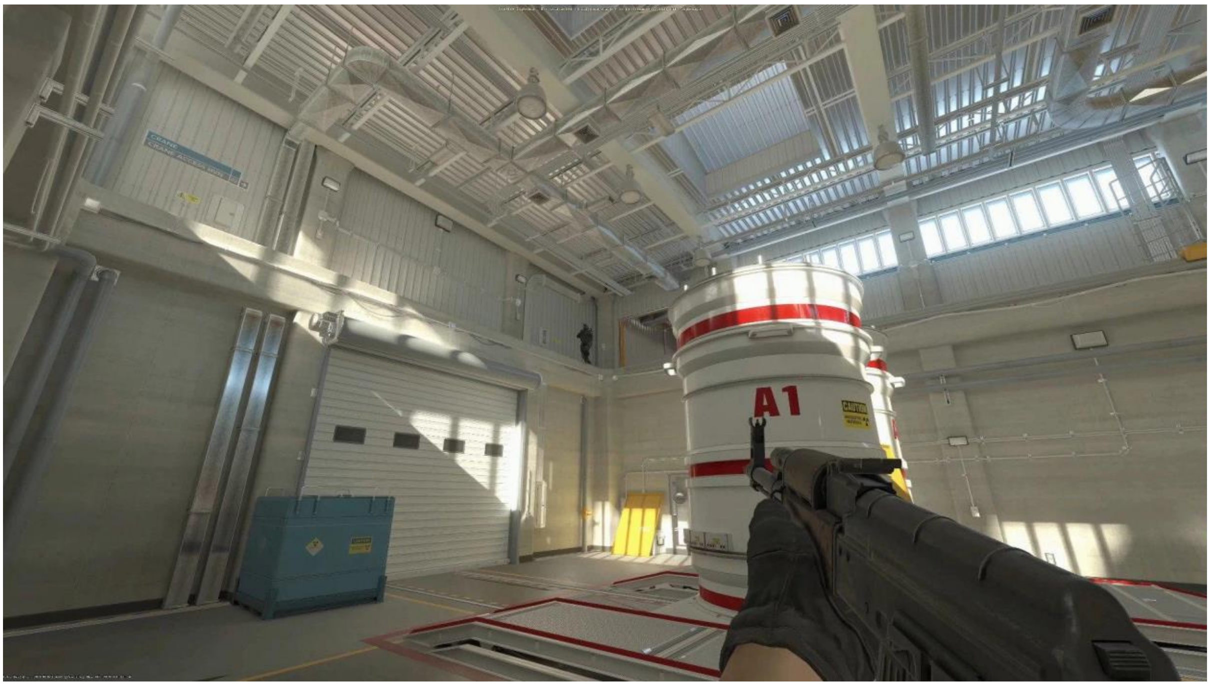


Figure 5, Image of Counter Strike 2 Visuals.

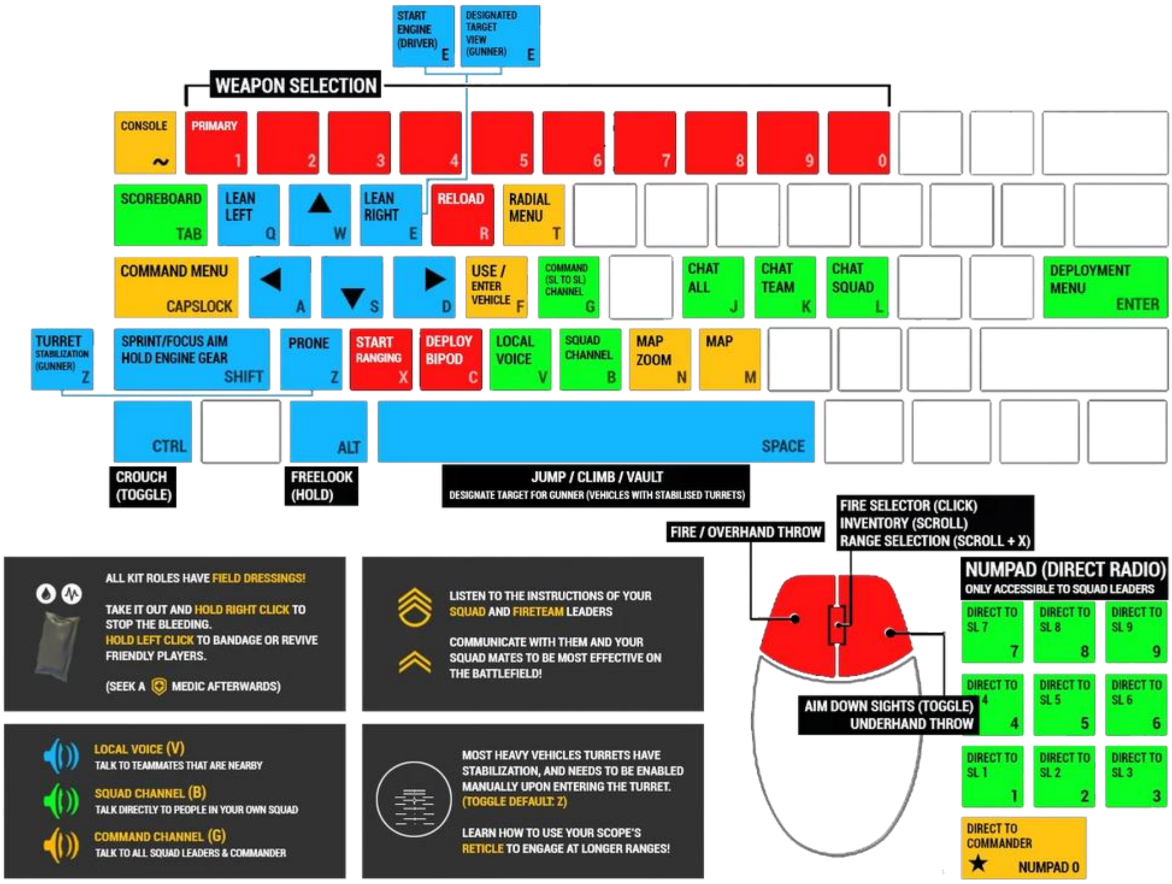


Figure 6, Mouse and Keyboard layout for Counter Strike 2 controls.

The rewards offered from gamification, be it a title, a trophy, a fancy sound, or even modified aesthetics, tend to only engage the person playing for as long as the gamification continues (Ahtinen et al., 2010; Garde et al., 2015; Koivisto & Hamari, 2014; Lentelink et al., 2013; Munson & Consolvo, 2012; Zuckerman & Gal-Oz, 2014) and this is corroborated via SDT (Gagné & Deci, 2005). This means the game must have an ever expanding and evolving set of rewards for the player, which means continued associated costs for continual support of the game. A drawback noted by Sardi et al. (2017) was relying on only one form of gamified reward, for example, increasing a level, and quickly fatiguing the player, requiring a diverse set of rewards for a person to work towards. This is, of course, assuming all people are playing with good intent. It would not be unreasonable for the person being rehabilitated, if the clinician and the game purely focus on the end goal, for the person to also focus on the end goal: to feed results into the game that the game wants without actually doing any of the work, in other words, cheating, which has been discussed as a large downside to gamification (Pereira et al., 2012).

It can be extremely difficult to completely eliminate any method of cheating. It is better to encourage good faith engagement and implement a few rudimentary anti cheat measures following the “Swiss —cheese” methodology (Larouzee & Le Coze, 2020). Such measures could include away-from-keyboard (AFK) detection, recognising objects in complex images, similar to captcha, or even requiring more effort to cheat than the reward would be. These methods can be relatively easy to implement and would be able to catch many instances of malicious behaviour but depend on the gamification in question, see Lehtonen (2020) for an overview on modern anti-cheat methods. Extending the study done by Patel et al. (2017), where patients’ steps were counted via wrist Fitbit or mobile phone app, cheating could occur by repeatedly jiggling the device in question. To counteract this, they may need GPS (global positioning satellite) data to verify movement is happening and below a certain speed threshold (to rule out motorised transport). This would limit most cheating opportunities to driving around slowly, which comes with a larger time and financial (fuel) cost. Patel et al. (2017) also had minimal extrinsic rewards for scoring highly, each gold or platinum family would receive special mugs, utilising an anti-cheat method whereby the reward is less useful than the resources expended to cheat to attain it.

1.3.4 Design Constraints of Gamification

There is a technological and fiscal barrier to the people that play these games: they must have sufficient computing and graphical power to play the game, with a desktop PC meeting the minimum system requirements for 99% of games retailing for a minimum of £1000 (Lab, 2024). One way around these barriers is to go for a modality with very standardised hardware such as a console or phone or to develop a game with extremely low system requirements, meaning essentially any piece of hardware could play it. Current generation consoles have retail prices in the hundreds of pounds, as do virtual reality headsets, and mobile phones. Consoles have the added caveat of requiring a television, although most households will already have one of sufficient quality. Virtual reality headsets require an area clear of obstructions, which can be difficult to come by in some house configurations and also accompany a minor risk of injury via walking into or knocking things. Mobile phones have a similar price barrier to virtual reality headsets and consoles; however, most people already have one (97% in USA, (Center, 2024)), making cost a non-issue since it has already been paid. Whilst mobile phones appear to have the lowest cost barrier, the user interface presents additional design problems: the screen is relatively small compared to other modalities; only takes up a fraction of the visual space; and the buttons must be limited in size due to the size of the finger and sensitivity of the screen. There are also issues concerning battery life and heating of the phone, which pose issues to time consuming rehabilitation programmes, along with the risk of distraction if the person does the rehabilitation in a public space.

The alternative solution, by having very low system requirements, has its own drawbacks. This will typically manifest as less detailed in game assets, and less objects in the game environment. Prior research has revealed stronger effects when people playing the game feel embodied, that is, as if the in-game avatar or persona is close to or one with themselves (Ash, 2016; Ratan & Sah, 2015; Sherrick et al., 2014; Yee & Bailenson, 2007), although a recent overview by Liu (2023) questions the validity of some of these findings. By having lower quality game assets, people could be pulled away from the game, lowering embodiment and resulting in a less strong effect. On the other hand, high quality game assets come with large storage requirements, with an egregious case being Call of Duty 3 which is in excess of 200GB (IGN, 2023), most of which is the high-quality texture, model, and sound assets. Lowering requirements would result in a benefit to the person with rehabilitation since it would be able to be easily stored on most devices and have no attendant opportunity cost of a different application that was removed for the rehabilitation one.

Not only is the hardware barrier a very real concern with difficult trade-offs for every modality, but the software itself is a barrier. Some forays into gamification have used pre-existing games e.g. Verdecchia et al. (2014). What this means, is that the games chosen for gamification of treatment, are made with the primary purpose of user engagement and monetization. Creating bespoke software from scratch can be incredibly difficult, depending upon the requirements and involves leading a team of multi-disciplinary workers, such as artists, developers, and level designers (Aleem et al., 2016). Apart from the aforementioned visual complexity and game difficulty mismatch, pre-existing games are incredibly unlikely to be able to isolate the visual stimulation required to habituate symptoms on demand; that is, certain gameplay elements must be triggered to get the requisite visuals. As an example, if a spell in World of Warcraft were required to habituate due to their visual aspect, there is an issue because each of spell has an associated cost, lockout time, and usually requires a target (Bardzell et al., 2012; Suznjevic et al., 2008). See figure 7 as an example of how different the visuals can be within a single game, with figure 7A requiring many hours of investment to achieve, and figure 7B requiring minimal time investment. This means that any time spent on rehabilitation would be nonlinear, requiring a much larger time budget for the person rehabilitating, as a lot of the time would be spent setting up the required conditions for the visual stimulation to occur. The main drawbacks of developing a game for rehabilitation, is the requisite cost and time associated with development.

Figure 7, example of a visually triggering (top) vs a non-triggering (bottom) scenario from World of Warcraft.

1.3.5 How can Gamification Work with Visually Induced Dizziness?

One of the large issues with visually induced dizziness rehabilitation, is that the visuals shown in the game are the rehabilitation. This means that for almost all currently available games the gameplay would be intrinsically linked to the rehabilitation. For example, in counter- strike two, the game is more difficult if you are facing more enemies. However, more enemies means that there will be more things on the screen, which means the screen has more visual complexity on it which could be too severe for a person and their rehabilitation. This holds true for essentially any game; difficulty is typically increased by getting the player to contend with more things (Aponte et al., 2009). Any developed vestibular rehabilitation game tool must, therefore, find a way to break this link between the visuals shown on the screen and the gameplay. If this is not done, a person could find the game far too easy or far too difficult for their symptom load and their gameplay difficulty load. This would completely defeat the point of gamification to increase engagement, as the person would be unable to alter the gameplay to suit their needs due to the rehabilitation requirements.

We also know that there are other factors which tend to increase the effect that game situation can have, such as the amount of embodiment a person feels towards their game avatar, if there is one (Ash, 2016; Guegan et al., 2016; Li et al., 2014; Ratan & Sah, 2015; Ratan & Dawson, 2016; Sherrick et al., 2014; Yee & Bailenson, 2007; Yee & Bailenson, 2009). One notable exception to this can be puzzle games. A puzzle game must have recognisable puzzle pieces, and the game environment. Whilst puzzle difficulty can be modulated visually, see Ribelles et al. (2024) or Laakso (2019), they do not need to be. As long as the player can recognise and differentiate between the two, it does not matter what they are. The puzzle complexity can then be independently adjusted compared to the game environment visual complexity, providing an elegant solution to the visually induced dizziness game complexity issue. However, this does not guarantee that a person would find the game engaging: they may dislike puzzles, or how the current puzzle was implemented. Prior research revealed it is much cheaper to offer meaningful feedback about rehabilitation (Zuckerman & Gal-Oz, 2014), however, sometimes it can be difficult to know what information to feed back to people. A daily step goal, progress towards that goal, with continuous tracking of that progress is simple to do for walking and step goal increases. When applying this to visually induced dizziness and habituation rehabilitation, it becomes less easy to feedback a clear progress metric. As previously mentioned, there is no clear test for visually induced dizziness and current measurements have issues, for example Yip and Strupp (2018) and Powell, Derry-Sumner, Rajenderkumar, et al. (2020) show issues with scores for the dizziness handicap inventory and the visual vertigo analogue scale, respectively. Symptoms can vary day-to-day and are not present on every day (Staab et al., 2017), making daily goals less viable as they could be too easy one day and too difficult the next. Symptom triggers are also quite heterogeneous (Popkirov, Staab, et al., 2018), making a universal guide a-la step-count non-viable for some people. This leaves virtual rewards and social comparisons to encourage motivation as a more viable gamification route.

One of the other mentioned issues with visually induced dizziness and rehabilitation is whether a patient is doing the rehabilitation exercise correctly. Utilising a real-world gamification paradigm as in Patel et al. (2017) would be non-viable as it would require either self-assessment by the person, defeating the purpose of solving this issue, or extensive video review by a clinician which has a whole host of time and safety issues. As such, any rehabilitation is required to be software based. As a result, the software can simply not allow the person to do the rehabilitation incorrectly. This guarantees that not only does the person do the rehabilitation in the correct manner, but every person is getting the same standard of care. This second point, about standard of care, is especially useful when it comes time for a clinician to review progress. Not only will the clinician know that they have had the same standard of care, and correctly done the exercises, but the software can also track when, and what, rehabilitation did occur, removing the need for the person to manually note or remember this information. There is also ample evidence to support the notion that gamification will also bring forth, at minimum, short term engagement benefits (Rodrigues et al., 2022). If people see, or feel there are, benefits to the rehabilitation, this will then keep them engaged long term, thus solving engagement in vestibular rehabilitation.

1.4 Ethical Concerns

There are ethical concerns when it comes to gamifying visually induced dizziness rehabilitation. This is due to habituation being an unpleasant experience (Benito & Walther, 2015). People would be asked to play a game, with the design of Balance-Land being based on established, evidence-based, principles, yet there being no initial evidence playing Balance-Land would rehabilitate symptoms. Additionally, Balance-Land has been designed to trigger their symptoms, which would likely result in feelings of dizziness, nausea, or visual discomfort. Care must be taken to only trigger symptoms to the minimum required level to achieve habituation rehabilitation, not only due to ethical concerns, but also because people that experience large symptom loads from rehabilitation are less likely to continue than those that don't (Gamble, 2022).

1.5 Where do we Start with Balance-Land?

Balance-Land is the name given to the gamified rehabilitation software for visually induced dizziness that was developed during this PhD. Initially, it was unclear whether an existing game (already gamified) should be taken and adapted to aid rehabilitation, or whether rehabilitation instead should be taken and gamified. The issues identified in sections 1.3.4 and 1.3.5 led to the conclusion that utilising an existing game has too many drawbacks in terms of rehabilitation benefit and, as a result, a custom game must be developed. Research has shown that older adults tend to prefer games that are easy to learn and play but are challenging (Salmon et al., 2017). Two genres of games that fit this definition would be strategy games, and puzzles games, one of which has already been noted to be ideal for rehabilitation of visually induced dizziness. Unfortunately, Salmon et al. (2017) also found that older adults tended to play alone, meaning that it may be more difficult to naturally find social motivation gamification cues to aid with motivation and engagement. A different study found older adults (65+) preferred casual puzzle games and rated them 0.95 out of 1.00 (Chesham et al., 2017), supporting Salmon et al. (2017). Whilst these cohorts are slightly older than the age commonly found for visually induced dizziness (Dieterich et al., 2016; Neuhauser, 2016; Strupp, 2003), many people with PPPD have been unable to rehabilitate effectively and have symptoms persisting years (Nada et al., 2019), putting potential participants in this age range.

A puzzle game as a starting point works well, keeping gameplay and game visuals separate from each other. Initial gamification elements will be kept minimal, as there is currently no evidence Balance-Land would aid with rehabilitation and it is not ideal to encourage participants to play a harmful game with no benefit. The aforementioned lack of social gaming (Salmon et al., 2017) leaves points as the initial best starting point, as collecting puzzles can be reinforced via point gains. A large part of vestibular rehabilitation will be the complex visual elements (Law et al., 2024), which can be included by having puzzle pieces randomly distributed in a virtual environment. This forces participants to experience visual flow and complex visuals by moving through the environment. Taking lessons from prior gamification studies (Beltran et al., 2012; Imbeault et al., 2011; Schönauer et al., 2011) input and movement must be kept minimal and streamlined. Other studies of vestibular rehabilitation e.g. Riccelli et al. (2017) have demonstrated the efficacy of “on-rails” visual stimulation, finding it effective at rehabilitation. As a result, this can be co-opted into Balance-Land, with the additional benefit of ensuring that all visuals will be identical between participants, making comparisons of rehabilitation efficacy easier. What controls are put on the screen may be interacted with via left-click.

When determining what environments to include within the puzzle game, we must look at what participants want. Prior evidence has noted the risk of overstimulation (Gans, 2015) meaning there must be a variety of stimulation levels to choose from, which should incorporate known situations participants struggle with and aspire towards overcoming. The most obvious of these environments would be a supermarket, partially due to the long history of the supermarket being a stimulating environment (Cordes, 1872; McCabe, 1975; Westphal, 1871) and partially due to it being necessary to visit. Participants would be able to have a clear and direct target to work toward. However, a supermarket will be very stimulating for participants, even in a safe and less-stimulating manner. To counteract this, an environment of minimum visual complexity should be a starting point. Open sky is minimally triggering, as it has very low contrast and little, if no, discernible shapes. This provides the minimal starting environment. Jumping from this to a supermarket would be a large change, so an intermediate environment should be implemented. To provide contrast to the artificiality of the supermarket, and because naturalistic environments are less triggering for visually induced dizziness (O’Hare & Hibbard, 2011), and due to feedback from an initial participant panel whom reported not liking walking through a forest with tress, the third initial environment will be based off a forest.

Taken together, this makes Balance-Land a puzzle game with three initial environments: open sky, forest, and a supermarket. These should provide sufficient stimulation for a variety of symptom intensities of visually induced dizziness, with speed controls providing a modulator for visual flow. Controls will be simple, with only a left-click being required to interact with Balance-Land. Points will be rewarded for successfully completing game tasks, which involves exploring the environments to make words. This means the points encourage movement through the game environments, which is the basis of the vestibular rehabilitation. As a result, a participant wanting more points will experience more complex visuals and thus should, theoretically, effectively rehabilitate themselves: the gamification reward directly aligns with the desired vestibular outcomes. Additional gamification elements can be implemented as evidence around the efficacy of rehabilitation emerges.

1.6 Summary

Visually induced a dizziness is a prominent feature of PPPD, vestibular neuritis, Ménière's Disease, and vestibular migraine (Bisdorff et al., 2015; Law et al., 2024; Popkirov, Staab, et al., 2018; Staab et al., 2017), drastically decreasing the quality of life of the people it affects. The aetiology of PPPD is unclear (Staab, 2023). However, there are treatments that appear to work (Axer et al., 2020; Byun et al., 2021; Popkirov, Stone, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023). Current treatment has issues that need to be improved: people must be able to adjust their rehabilitation to the symptom severity and needs; people should be able to more easily engage with treatment so that they are more likely to adhere and as a result of rehabilitate; treatment should be very easily accessible, so that a person is never wondering if they are doing it correctly or how to do it at all; and most importantly, treatment should actually reduce the symptom level.

Our goal is to develop a game-based intervention for visually induced dizziness: Balance-Land. There is a lack of accessible and effective visual desensitisation rehabilitation that allows participants to customise their treatment and remain motivated. As such, Chapter 2 starts with a user-centred approach and will detail the first pilot of the game which had questions such as “will symptoms be triggered”. Chapter 3 continues the user-centred design and moves into how we can better change and personalise the game for the participants, going on to talk with participants and vestibular clinicians about how to best help participants. Chapter 4 then moves into our first larger-scale study, a feasibility study, where we recruit from around the world in a very ecologically valid study to determine whether Balance-Land is feasible as a form of rehabilitation for visually induced dizziness. Chapter 5 delves into the gameplay data of participants from the feasibility study, aiming to determine whether any of the gameplay and behavioural data can explain any of the findings from Chapter 4. And finally, chapter 6, will detail final improvements we have made from feedback in Chapters 4 and 5 and the general discussion for what we have found.

2 Chapter 2: Balance-Land: a gamified rehabilitation program for people with Visually Induced Dizziness (VID)

The next two chapters were written in the style of Computer Science papers. As such, they will have a focus on the development and impact of Balance-Land.

2.1 Introduction

People with visually induced dizziness (VID) experience symptoms of dizziness, unsteadiness, and non-spinning vertigo that are exacerbated by motion, complex visual environments, and upright posture (Staab et al., 2017). VID, or 'visual vertigo', occurs in vestibular migraine, Meniere's Disease, traumatic brain injury (TBI) and persistent postural-perceptual dizziness (PPPD), the leading cause of functional dizziness (Staab et al., 2017). VID exists on a spectrum in the healthy population (Powell, Derry-Sumner, Rajenderkumar, et al., 2020). Anxiety is a common occurrence in people with VID, with patients often fearing environments that are likely to trigger symptoms (Popkirov, Staab, et al., 2018). Vestibular rehabilitation and visual desensitization is the main treatment approach (Popkirov, Stone, et al., 2018), but is often unenjoyable because it is repetitive and triggers symptoms (Popkirov, Stone, et al., 2018; Staab, 2012). Additionally, such exercises do not help to expose patients to environments they fear in the real world, and it can be difficult for clinicians to know rehabilitation schedules are being adhered to.

These issues might be solved via gamification, which is the selective incorporation of game elements into a system (Deterding, 2012). In essence, gamification of vestibular rehabilitation would involve enhancing rehabilitation efficacy via motivational affordances (Huotari & Hamari, 2012). Gamification has shown successful outcomes in other healthcare settings, including physical activity, nutrition, hygiene, and medication adherence (Hamari et al., 2014; Pereira et al., 2014).

In this study, we report the development of Balance-Land, a web-based rehabilitation game for visually induced dizziness. Balance-Land aims to rehabilitate symptoms of

VID through habituation to visually complex stimuli with high-contrast, repeated patterns and visual flow (Popkirov, Stone, et al., 2018). Habituation involves exposing the person to small quantities of the triggering stimuli in a safe and controlled manner, until their reaction to the stimuli attenuates (McDonnell & Hillier, 2015).

The game was developed during three phases of iterative feedback with people with VID and clinicians. Our development challenge was to create a web-based VID rehabilitation program that delivered visual stimulation at a tolerable level, packaged in an engaging format that individuals with lower video game experience could play across a range of devices. Unlike off-the-shelf solutions such as the Wii-fit, we wanted to provide flexibility over intensity of therapeutic stimulation and allow patients access to virtual environments that they fear in the real world (e.g. supermarkets (McCabe, 1975).

2.2 Related Work

Vestibular rehabilitation can take many forms, but the overall ethos is to recalibrate the visuo-vestibular systems, and particularly in the case of visually induced dizziness, to desensitize the patient to visual input and build confidence to feared environments. Clinical guidelines recommend a duration of 12 to 40 minutes per day, depending on the type and severity of the vestibular condition (Chesham et al., 2017). Vestibular rehabilitation can include exercises such as following a moving finger with the eyes or moving the head in different planes of motion. These exercises can be done easily at home without the need for any additional equipment or technology, but the exercises are not engaging and elicit dizziness. Therefore, adherence is low. Additional options include passively watching videos containing intense visual stimulation, which has been shown to reduce VID symptoms (Pavlou et al., 2013). However, attrition was found to be high if participants were left to watch the videos unsupervised (55%) (Pavlou et al., 2013). Therefore, including a task or game to motivate participants while they are watching the videos might increase engagement.

Other researchers have explored using off-the-shelf video games for rehabilitation purposes, such as the Wii fit balance board (Jones & Thiruvathukal, 2012; Verdecchia et al., 2014), getting participants to play Wii games biweekly for 20 minutes. The advantages of using the Wii were not just that the game element increases engagement, but it also encourages the participant to move, which likely aids sensory-motor recalibration. One study has reported such improvement (Verdecchia et al., 2014) when participants played Wii sports, bicycle, platforms, tilting, and target practice. However, for people with more severe VID symptoms, the Wii would not be suitable because visual stimulation is too great, and there is no option to iteratively increase the therapeutic intensity from a low initial level. For many patients it would be potentially hazardous due to the risk of falls or vomiting. Many off-the-shelf video games also require players to learn how to use complex movement controls, which can be challenging for demographics with lower levels of video game experience. There is also no option customize environments to the individual needs of patients, e.g. if a patient needs confidence building by exposure to a supermarket.

Nevertheless, there are advantages of including a gamification element into vestibular rehabilitation, which have been shown in previous work. For example, a randomized control trial (RCT) (Micarelli et al., 2019) has shown that a virtual reality rehabilitation racing game improved symptoms for patients with unilateral vestibular hypofunction. Similar to Micarelli et al. (2019), a D'Silva et al. (2023) found positive outcomes for vestibular hypofunction patients who were treated via gamified tablet exercises. However, D'Silva et al. (2023)required an extra sensor working in tandem with the tablet, limiting mainstream accessibility. Gamification has been used with concussion patients with vestibular symptoms to provide feedback to participants via gaze stabilization (Salisbury et al., 2018). These studies provide evidence that a gamified vestibular rehabilitation tool is more effective than a non-gamified one, potentially helping to overcome currently identified issues with vestibular rehabilitation, such as treatment adherence.

One of the main issues with many current options is that they either require complex controls or expensive hardware and are therefore unsuitable for many people with VID who are not typical video game players (Dieterich et al., 2016; Neuhauser, 2016; Strupp, 2003). On the other hand, more simply controlled games, such as puzzle games, have the advantage of being widely accessible across age groups and dexterity abilities (Chesham et al., 2017; Salmon et al., 2017), But they do not generally have the types of visual flow needed for visual desensitisation. Our aim therefore was to combine a simply played game with visual flow desensitisation. This has the added benefit of allowing the visuals needed for rehabilitation to be graded independently of the puzzle type and difficulty.

In summary, visual desensitization is a helpful form of rehabilitation for VID, and the main difficulty for such rehabilitation is adherence to rehabilitation schedule. Gamification could help with motivation; however, no game exists that is tailored to the unique needs of users with VID.

2.3 Balance-Land: Phase One

The concept was to create a puzzle game where items had to be collected within virtual environments suitable for rehabilitation (Figure 8). There were four main constraints on design: appropriate visuals for rehabilitation without excessive symptom provocation; usability by players with little experience; engaging gameplay for wide range of ages; wide digital accessibility without specialist or high-spec equipment.

2.3.1 Game Controls and ‘Make Words’

Balance-Land was created in the game engine BabylonJS (Catuhe, 2013) using Typescript (Bierman et al., 2014), which is a heavily typed form of JavaScript. Phase One only contained on game mode: Make Words. Letter tiles were randomly generated and placed in the environment to pick up, targeting a mean density of between 2 – 5 letter tiles per Island (minimum of 1) depending on settings selected. Each letter tile contained two pieces of information: the letter (e.g. ‘A’) and the point cost (e.g. ‘1’). If a participant successfully created a word with a letter tile, they were awarded the sum of the points of the letters. For example, the word “as” contains the letter “A” and the letter “S”, each worth ‘1’ point, for a total of 2 points (1 + 1 = 2 (Whitehead & Russell, 1927)). To verify if words created during play were real words, a database of the 10000 most common English words were used (Github, 2024). The top 10000 words were chosen to allow creative use of letters but not uncommon words that are more common as typographical errors (e.g. ‘Bath’ vs ‘Baht’ the Thai currency). Whenever a participant submitted a word (see Figure 8D), the word was checked against the repository and points were awarded if the word was found. If the word was not found in the repository, the participants would be informed the word was “not valid” and to try again.

Figure 8A shows the Main Menu where participants selected one of the three virtual environments (1) and a difficulty level or a tutorial (2). The feedback button (3) linked to a Qualtrics survey about their gameplay experience. The help button (4) brought up instructions for the main menu along with definitions for key terms such as: dizziness, nausea, and visual discomfort. Screenshots for all three virtual environments are shown in Figure 9*.*

The Sky environment is illustrated in Figure 8B; the top left (1) button was for settings, represented by the standard “cog” icon, and opened the settings menu (Figure 8C), where speed could be adjusted. The turn button (2) lets the user turn at the next turning. The start/stop button (3) lets participants start or stop moving with a single button press. If symptoms start to trigger and participants need to lower their stimulation level, this button was immediately available. The aim of the game is to collect letter tiles in the virtual worlds. And use them to make words in the Word Board (Figure 8D), which was accessed via button (4) In Figure 8B. The map button (5) opened up a top-down view of the playable environment (see Figure 10b). The Fullscreen button (6) sets the game to Fullscreen, which participants were asked to do due to field of view concerns.

Figure 8C shows the settings menu; swapping the side of the controls was for potential tablet or mobile phone users. The speed the participant moves at could be changed at any point via the sliders located in this settings menu. The speed for corners versus not-corners were different as turning different flow field. The units for speed were arbitrary but linear. A speed of ‘2’ (default) was twice as fast as ‘1’. The minimum allowed speed was ‘0’ (stationary), the maximum allowed speed was ‘10’, and the minimum allowed increment for speed was ‘0.1’.

Figure 8D shows the Word Board, which is where participants create letters in the game mode ‘Make Words’. The red row (1) is where participants place letters they wish to use when creating a word. The ‘bag’ of collected letters has a different, blue, background (2). Letters could be dragged and dropped between (1) and (2) or a participant could right-click on a tile to automatically move the letter between the two. The submit button (3) would concatenate all letters in the red row (1), removing all empty space, and check the resulting word against the repository (Github, 2024).

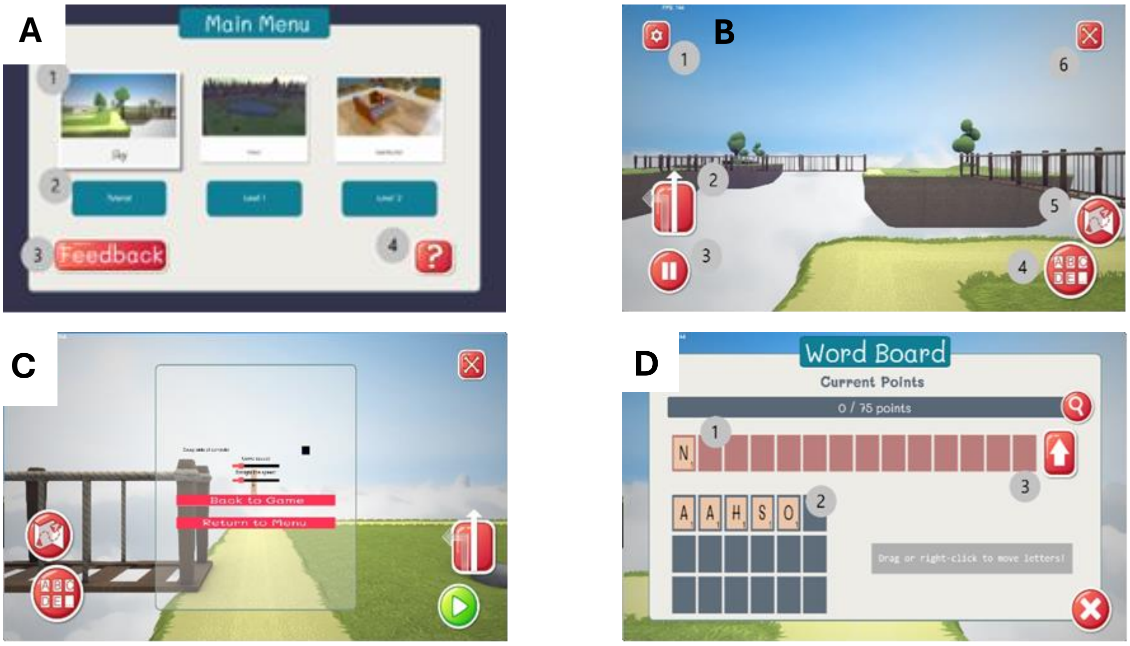


Figure 8, Figure 8A shows the Main Menu, 8B shows a screenshot of gameplay from ‘Sky’, 8C shows the Settings Menu, and 8D shows the Word Board.

The islands and corridors in Balance-Land were procedurally generated (see Figure 10). Procedural generation has been shown to be more engaging than having a static environment (Brewer, 2017) and would avoid participants repeatedly using one route. The maps were generated via creating a data array, randomly selecting indexes in the array to populate with rooms, then converting the data array to a cell array and creating random links between rooms with corridors (see Figure 10A). As illustrated in Figure 10B, the map view showed the participant location (the red triangle) along with all the tiles on the map. This allowed participants to plan out the words they want to create and calculate a route to desirable letters.

Figure 9, 9A (top left) is the Sky virtual environment. Figure 9B (top right) shows the Forest clearings and 9C (bottom left) shows the sunray effect on the Forest path available in Level 2. Figure 9D shows the Supermarket virtual environment.

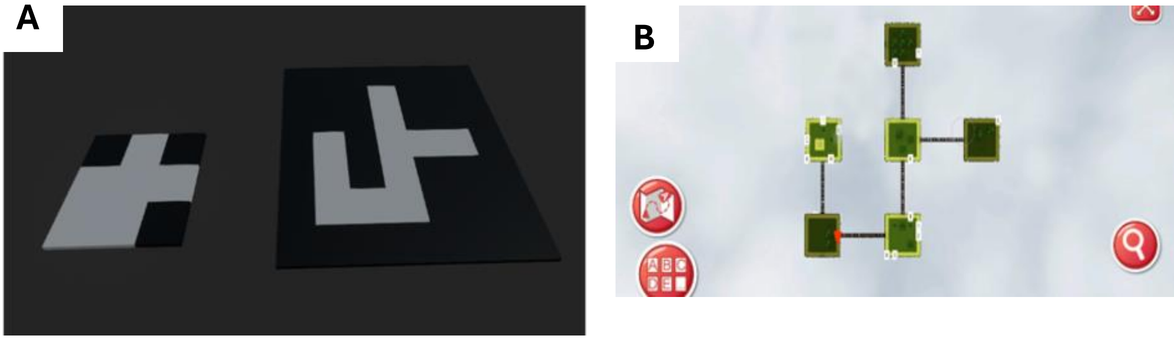


Figure 10, The data array (10A) with randomly selected index for rooms, compared to the cell array which then adds links between the rooms. 10B is a map view of the Sky environment, with textures implemented.

2.3.2 Balance-Land's Initial Design

To create visual flow suitable for desensitization, "first person" movement through simple virtual worlds was used, creating self-motion flow with different levels of speed, complexity and contrast to suit the severity of each patient's dizziness (rehabilitation must trigger symptoms at a manageable degree). The simplest environment ('Sky') is shown in Figure 8B (the environments and their construction are explained further below and in Figures 9 and 10). In order to create stable motion, a fundamental design choice was that movement would be via preset pathways and without free camera control. The motion flow field associated with simulated head-turns is highly symptom-provoking for patients, and as such this needed to be minimized within the virtual environments to allow rehabilitation at manageable symptom levels. Thus, movement was constrained to be on set pathways with straight-ahead view. This is also why we incorporated a separate speed control for corners (Figure 8C), where the flow field would be particularly difficult for patients.

A second key design choice was to ensure usability with highly simple game controls that did not rely on reaction time or multiple buttons or joystick controls, in order to be accessible to players with little or no digital experience. Therefore, movement was automatic and continued around one pathway until the ‘turn’ button (Figure 8B, button 2) was selected in order to move onto another pathway at the next encountered junction. Movement speed could be adjusted via the settings (button 1).

The third key design choice was to base gameplay on familiar word puzzles, potentially suitable for any adult age-group, and easily translated into another language via loading a different dictionary. Letter tiles were collected in the virtual worlds and were used in the ‘Word Board’ screen to make words (Figure 8D).

Lastly, for accessibility, we aimed to create a web-based browser game that could run on any device. This necessitated compromises on graphics and screen size / field of view, but the accessibility criterion was judged more important.

The aim of the three virtual environments (Figure 9) was to incrementally introduce more visual complexity and contrast. The game world was made up of three types of tiles: a Path, a Corner, or a Corridor. Each room was comprised of Paths and Corners, with corridors linking rooms. Sky (Figure 9A) was the least visually complex. The rooms were floating islands connected via corridors textured as bridges, the only background stimulation being a skybox. The lack of objects, a simple colour palette, soft lighting, and lack of straight lines on the islands should provide the low stimulation needed for most patients. The bridges were expected to be more visually challenging.

Forest (Figure 9B) was planned as the next stage in visual complexity. The floating islands were clearings surrounded by hedges or trees and the bridges were paths lined by trees. For the difficulty level 2 of Forest, there was a sunray effect added to the paths between islands (Figure 9C), which produces flicker as the player moves past the tress. This simulates a type of stimulus patients report as highly symptom provoking (Yoshimoto et al., 2020).

Supermarket (Figure 9D) was the most visually complex environment. Many people with VID describe a supermarket as one of the most triggering environments to be in. The islands were kiosks surrounded by shelves, with the bridges being aisles lined with shelves. As such, the Supermarket virtual environment aimed to simulate the combination of lighting, colours, object density and rigid lines that patients struggle with and need to desensitize to.

2.3.3 Ethical Concerns

To alleviate ethical concerns, all participants must be informed that symptoms will most likely be triggered. Specifics must be given as to what type of symptoms may be experienced, to what level, and what to do in the event that these symptoms become too unpleasant or the person experiencing them, that is, how to minimise the negative effects of the symptoms at that given moment. This would come in the form of what we call a coping strategy. Coping strategies will depend on the modality. However, there are some basic coping strategies that work for all modalities, such as closing one’s eyes. Closing one's eyes will immediately and dramatically reduce all visual input, meaning that any discomfort created from visual input should be greatly diminished. As such, participants were instructed to stop playing or close their eyes if they felt their symptoms were becoming too stimulating.

All procedures were approved by the Cardiff and Vale Health Board and the School of Psychology, ethics committee (NHS ethics, REC 13/WA/0119).

2.3.4 Design Approach: User-Centred Design

It was important that the game was designed to suit the needs of the end users: patients with PPPD / visual vertigo and audio-vestibular clinicians. User-centred design is an approach where users are involved in the design and development of a product (Abras et al., 2004). We took an iterative approach where users provided feedback on the game, which was followed by refinement, then another round of feedback and refinement. In total, there were three phases of game development. Two rounds of feedback involved patients (Phases 1 & 2) and one round involved clinicians (Phase 3).

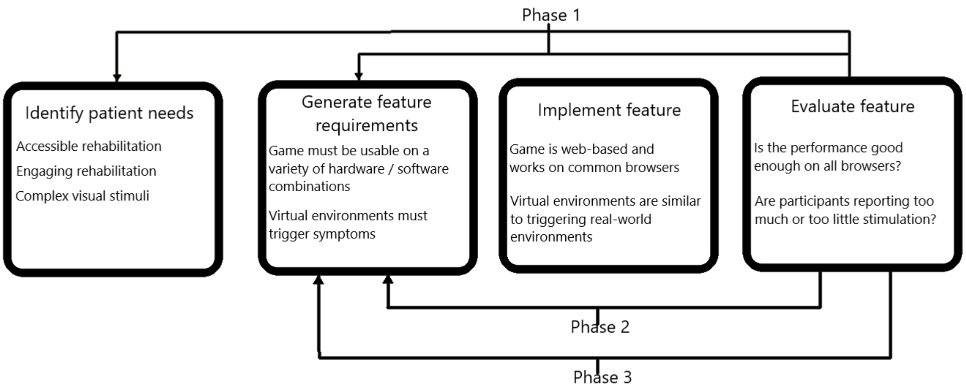


Figure 11, Illustration of the user-centric design approach. The examples given in each box illustrate the process for a subset of the features implemented in the game.

The aims of Phase 1 were to find whether the game was usable, accessible, and enjoyable. We wanted to ensure that the visual environments in the game triggered symptoms in a tolerable range (a predicted requirement for rehabilitation). We also asked patients for their suggestions for improvement. The game was then refined based on feedback from participants. In Phase 2, we tested whether the changes had been effective and investigated how patients saw the game potentially fitting into their life and rehabilitation plan. The flexibility of settings was increased within the game to better suit individual preferences. In Phase 3, we interviewed audio-vestibular clinicians to further improve the game design, find out how clinicians would envisage using the game in their practice, and determine the procedure for a future randomized controlled trial. See Chapter 3 for details on Phases 2 & 3.

2.3.5 Phase One: Methodology

The aim was threefold: to determine whether visually induced dizziness symptoms were evoked at an appropriate level; whether the user interface was considered usable; and whether participants found Balance-Land engaging, therefore increasing motivation to play.

Participants were instructed to play Balance-Land for as long as they wished and were asked to play as many different levels as they could. Whilst participants played Balance-Land, they were periodically asked one of four questions in-game: how dizzy they were; how nauseous they were; how much visual discomfort they were experiencing; or how much they were enjoying playing the game. All of these questions were based on a 5-point Likert scale, suitable for quick response within the user interface. For most analysis, the ratings for dizziness, nausea, and visual discomfort were combined into one “discomfort” score, as they are expected to strongly correlate (Staab et al., 2017); varying the question asked aimed to elicit less automatic responses and more thoughtful responses (Ertmer et al., 2011).

Participants were instructed to fill out an exit survey after they had finished, which contained: demographics, gameplay questions, and action ranking (participants ranked the unpleasantness of different in-game actions). Gameplay questions were a variety of quantitative questions such as rating on a scale of 0 to 10 (0 low and 10 high; an easily understandable scale, with enough range to allow for nuanced response (Royeen, 1985)) and open-ended qualitative questions to allow participants to fully express their experiences, with questions designed to gather a full range of feedback (Agee, 2009); e.g. “What did you like about the game?”; “What did you dislike about the game?”.

The amount of time participants spent in different parts of the game was recorded, along with how many words the participants successfully completed as well as whether they gained enough points to complete the level. This data allowed positive control confirmation that participants responses to survey questions reflected what they experienced, and whether participants actually engaged with all features of Balance-Land.

There were 11 participants that had both survey and in-game data, recruited a vestibular clinic at the University Hospital of Wales. The mean age was 53.5 years (± 9.2 years 1 standard deviation, range [14 - 61]). No participants provided gender information, likely due to a survey software issue. The participants did not appear to deviate from typically seen male:female ratios found in other literature (Formeister et al., 2018; Murphy et al., 2021; Ruckenstein & Staab, 2009). Ethical approval was acquired prior to data collection (NHS ethics, REC 13/WA/0119).

2.3.6 Phase One: User Feedback

Balance-Land was accessible as a platform: participants were able to follow a link to the game and play, with only one participant having minor framerate issues.

When asked whether they experienced symptoms or not post-gameplay: 9 participants reported dizziness, 8 reported visual discomfort, and 8 reported nausea. Only 1 participant reported experiencing none of the symptoms during the survey, but they did report symptoms on the in-game Likert scale. The mean range of Likert scale responses for each participant were from 1.9 to 4.2, evocation from “a little bit” to “a lot”, with only two participants (mean 4.2 & 3.6) falling outside the target of moderate symptom evocation.

In the post-game survey, when asked to rank order the level of symptoms triggered by each world, participants ranked Supermarket higher than Forest, and Forest higher than Sky, as we expected. However, in-game, unexpectedly, patients did not report clear differences in symptoms between the environments (Figure 12A, one-way repeated measures ANOVA showed no significant effect, $F_{2, 8}=2.1$, $p=0.22$). This was therefore a point to address in Phase Two.

We expected the visual flow in narrow corridors, crossing bridges (with high contrast gratings produced by the posts (O’Hare & Hibbard, 2011)) or turning corners to be more symptom-evoking than moving along an open straight path. This was broadly confirmed: post-game, corners and corridors, which were ranked above the paths, with the bridges in Sky, particularly highly ranked. The triggering effect of corridors/bridges can also be seen in the in-game data (Figure 12B). As expected, most participants reported faster speed settings induced more symptoms.

Ease of use (4.6/10) and clarity of instructions (5.4/10) were given moderate scores whilst smooth gameplay was given a high score (7.9), indicating some of the controls still need to be improved. When asked whether participants understood the instructions, 8 responded “yes” and 3 “no”, but 5 participants did not utilize the turn button, showing that either they did not fully understand or did not want to cross the bridges/corridors.

Gameplay time was on average 9 minutes and 45 seconds a session (± 13 minutes 10 seconds, 1 standard deviation, Figure 12D), with a mean 2.4 words per play session, meaning participants moved around picking up letters but not often making words.

Participants gave a low-to-moderate enjoyment rating of 3.4/10 after playing (Figure 12C), lower than the in-game rating, but positively correlated ($r(9) = 0.89$, $p = 0.00$, 95% CI [0.49, 0.99]). Follow-up questions confirmed participants reported enjoyment lower due to triggered symptoms. However, both survey ($r(9) = 0.69$, $p = 0.04$, 95% CI [-0.25, 0.97]) and in-game enjoyment ($r(9) = 0.735$, $p = 0.02$, 95% CI [0.15, 0.98]) correlated positively with nausea, which may mean that those enjoying the game were less likely to minimize their feelings of nausea; Paradoxically, this could create a concern if participants find Balance-Land too engaging: if participants play too much initially, and trigger symptoms too strongly, this could reduce re-engagement according to a spaced rehabilitation schedule.

Qualitative responses about symptoms and usability were consistent with the ratings described above, showing that symptoms were broadly manageable, but instructions, controls and speed settings needed to be clearer for some players. In terms of engagement, we recognized that the main motivation to play was to aid research into PPPD rehabilitation, rather than to play computer games: "*to aid [a researcher]*", "*to aid recovery and help with the research*", "*happy to help studies*", "*I would do anything to aid my PPPD rehabilitation*", "*I hate computer games sorry*", "*I did not like it*".

Most revealing were unprompted comments about anxiety, especially for the sky world: "I [didn't] like the rope bridge – that made me feel very anxious and unsteady", "the feeling that I was very close to an edge that I could fall off", "I [didn't] like that the path [was] on the edge – I had a constant feeling that I was going to fall off the edge and it made me feel anxious and very unsteady", "I liked that it showed, on Sky game, coming to the end of a path and nothing there. That got me because I don't like heights. But I carried on and then felt better about it. The bridges. I find in real life I can't walk comfortably over a bridge. This game got me to feel better about it". These responses show that the sky environment may need to be changed for many participants, but also initial hints that gameplay may be able to boost confidence for anxiety-provoking real-world environments.

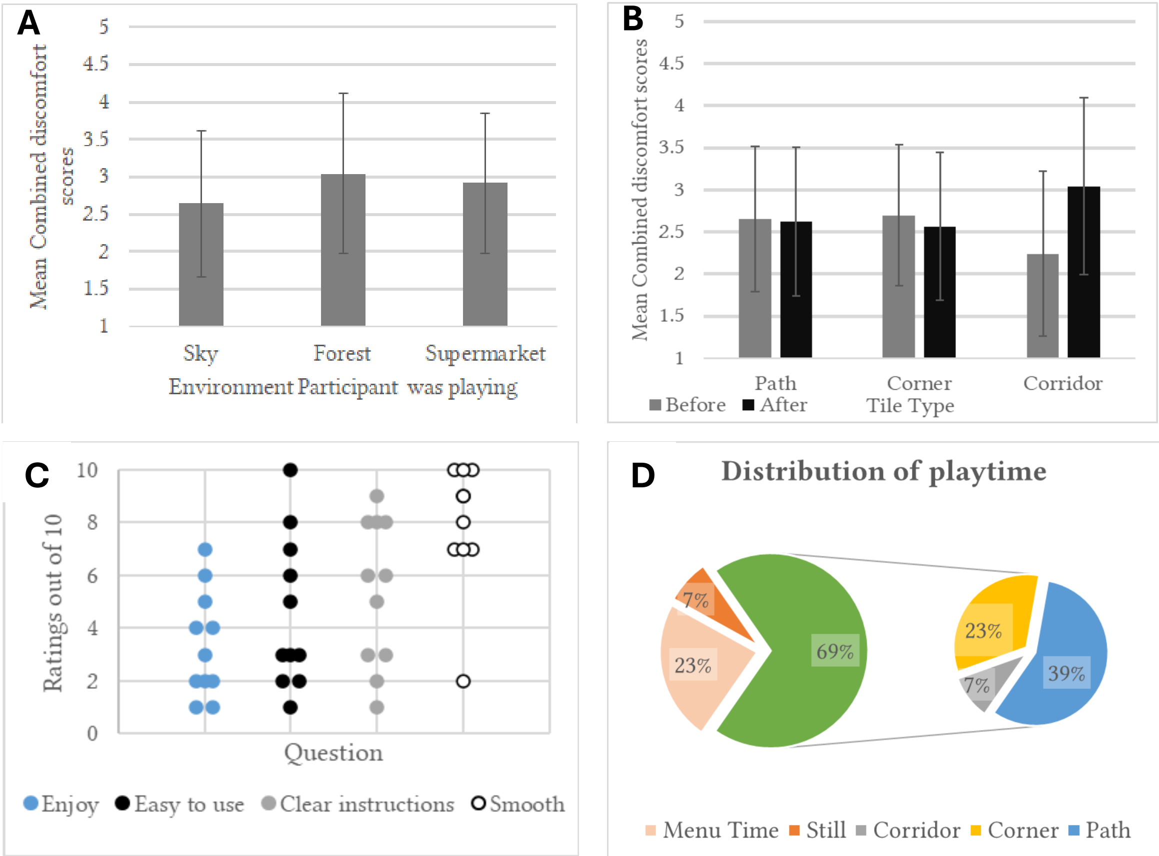


Figure 12,12A is the mean discomfort score for each participant in each environment. Figure 12B shows the mean scores before and after each specific tile segment. Figure 12C shows the scores out of 10 (10 high) participants gave in the post-game survey. Figure 12D shows the percentage of time spent by participants for each activity, the green segment is the sum of the yellow, blue, and grey segments (total movement time). Error bars are one standard deviation. n = 11 for all data except n= 6 for corridor data in 12B.

2.4 Phase One: Discussion

Balance-Land was able to evoke symptoms, was immediately useable by the participants with no training, and had moderate enjoyment levels, meaning Phase 1 hit all initial targets. Ratings for discomfort were only done in-game, and not prior to gameplay, meaning conclusions about discomfort ratings being caused by Balance-Land cannot be reached, but post-game comments indicated elevated symptoms as a result of playing Balance-Land. In-game ratings demonstrated discomfort were at a moderate level, which was the target. Post-game ratings of ease of use revealed participants thought Balance-Land was moderately easy to use, with clear instructions. Finally, Balance-Land had low-to-moderate enjoyment ratings, which was clarified in follow-up questions as being rated lower due to symptom triggers bringing the enjoyment rating down. However, this was juxtaposed by the participant's expression of being willing to play Balance-Land regardless of enjoyment if there was evidence of rehabilitation, potentially meaning as long as Balance-Land is not unenjoyable to play, rehabilitation will be enough to motivate participants to play.

There was no evidence the differing environments were able to differentially trigger symptoms, as initially predicted. With such a small sample size, this was not unexpected. Looking into the participant's comments, no participant explicitly called out any particular environment as being worse or more triggering than another. These findings echo Pavlou et al. (2013), with visually complex stimuli triggering symptoms, with rehabilitative results expected if there was a longer-term study with Balance-Land. A longer-term study still requires more evidence on what aspects of Balance-Land are useful and wanted by participants and more information on the target duration and periodicity of Balance-Land, as recent research has found no optimal duration or frequency (Law et al., 2024). When not focusing on symptom triggers, participant's comments about Sky highlighted the anxiety-provoking aspect of falling that was previously not considered, which could have increased discomfort scores in Sky. Whilst the fear of falling was not specifically considered, anxiety provocation was aimed as a secondary goal to further rehabilitation (Popkirov, Stone, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023), as visual dependence (Maire et al., 2017) may not wholly explain the symptoms of visually induced dizziness and targeting dizziness-related anxiety has promising prospects as another form of rehabilitation (Herdman et al., 2022). Participants also commented that more realistic environments would be preferable to stylistic ones, which aligns with the researcher's thoughts. This comes at a computational cost and must be tested whether participant's laptops and PCs would be able to handle the increased graphical demands. Currently, only the frames-per-second (FPS) were tracked for participants. Due to how Balance-Land was designed, it was expected that all participants would hit the FPS cap of 30. This was true, with the only time single-digit FPSs recorded when a level was being loaded, during which the participants were shown a loading screen resulting in no noticeable FPS dips. If the framerate drops to a level which participants no longer view smooth motion, participants would experience a strong symptom response, similar to simulator sickness (Saredakis et al., 2020). Simulator sickness is most often associated with 3-dimensional or virtual reality exposure but can also be found in 2-dimensional games (Chang et al., 2013). This would be undesirable, as the evoked symptoms would likely be above the moderate symptom threshold that Balance-Land targeted.

Whilst participants rated the instructions and ease-of-use as moderate, the in-game data revealed that only 6 of the 11 participants were able to turn off their initial island. When checking discomfort scores by the specific participant location within an environment, there was no evidence the location altered the discomfort scores, but the numerical difference for corridors, along with participant comments, indicates the corridor sections may have been more triggering compared to the other two location types (path, corner). One cause of this could be the aforementioned anxiety response induced in some participants, but was more likely to be because the corridors on Sky mimicked high-contrast visual gratings (see figure 9A) which are known to trigger symptoms (Popkirov, Staab, et al., 2018; Staab, 2023; Staab et al., 2017) and similar to prior stimuli in other studies (Pavlou et al., 2013). This demonstrates the ease-of-use and discomfort ratings may not be as reliable as initially thought, as participants were only rating what they were aware of. This means in Phase 2 and onwards there must be an effort made to adequately inform participants as to the whole scope of what is available to them. This can also be achieved through better user interface design, removing unnecessary buttons and making buttons temporarily relevant to their action. For example, in Phase 1, the turn button would (most of the time) do nothing when immediately pressed, which can be altered to a button only being useable when it matters, i.e. when a turning is available.

Enjoyment may have been impacted not only by the triggering of symptoms, but also by the ability of participants to understand the controls. It would be likely that participants that were unable to turn to other islands to create more words would rate enjoyment lower than those that did not (as is the case). This means the enjoyment scores were lowered by at least two factors yet were still able to result in a moderate score. Comments from participants indicated some of them would find playing Balance-Land less enjoyable over longer periods of time, such as that required for rehabilitation, meaning we must ensure motivation will be maintained longer-term. It should be noted that enjoyment is only one avenue to keep participants motivated, and there were multiple comments from participants stating they would be highly motivated to play Balance-Land if they were fed back information that indicated Balance-Land was having a positive effect on their symptoms. It is unclear what form this information should take, as other measures utilised for recording visually induced dizziness symptom severity such as the visual vertigo analogue scale (Dannenbaum et al., 2011), dizziness handicap inventory (Jacobson & Newman, 1990), or the Niigata PPPD questionnaire (Yagi et al., 2019; Yagi et al., 2021) could not be given to participants as often as they partake in vestibular rehabilitation (multiple times daily). This opens up a new inquiry as to which type of information can be easily gathered from participants and be useful to report. Regardless, the participants having less enjoyment as a result of being unable to use all game features due to not understanding the controls can be achieved via alteration of the user interface. Longer term motivation and enjoyment should be improved with additions to the game mode variety (currently only one) and environment variety (currently only three).

2.5 Conclusions and future work

Balance-Land aims to be a web-based tool for visually induced dizziness rehabilitation. Participants reported evocation of vestibular symptoms to a moderate degree, over half of participants needed no control instructions, and moderate enjoyment was reported. Concerns were raised by participants about longer-term enjoyment in Balance-Land, with some thinking the one game mode would become less enjoyable over time. Participants also reported that enjoyment was a secondary concern to whether Balance-Land positively affected symptoms. This gives clear targets for iteration in Phase 2: for the shorter-term, cleaning up the user interface of extraneous or non-responsive buttons and implementing new game modes and game environments; for the longer-term, feedback information to the participants that captures their rehabilitation progress and focus on altering the underlying structure of Balance-Land to convey more realistic environments. Even though there were clear avenues for future changes, Balance-Land in its current state fulfils the criteria for effective vestibular rehabilitation and should only continue to improve.

2.6 Acknowledgements

We would like to thank all the participants for providing their time and crucial input into the development of Balance-Land. A special thanks also to Mark Brown for his feedback. We also thank our community engagement panel for their thoughtful advice over the years and help in naming the game. This research was funded by Wellcome [104943/Z/14/Z] and Wellcome and Cardiff University ISSF [097824/Z/11/Z].

3 Chapter 3: Iterating on Balance-Land

3.1 Introduction

Visually induced dizziness (VID) is triggered by complex, large field, or moving stimuli (Bisdorff et al., 2015). Phase 1 provided initial evidence for Balance-Land as a tool for vestibular rehabilitation: symptoms were evoked at a moderate level; most participants immediately understood the controls; and was moderately enjoyable. However, there were clear issues raised by the participants that can be iterated upon, namely the ease of use and clarity of the controls. Though symptoms were evoked to a moderate degree, it was not clear what aspects of Balance-Land were causing the symptom evocations: it could have been driven by the visual flow, the complex visuals, anxiety-related, or more. Any of these can be sufficient to trigger symptoms of visually induced dizziness (Bisdorff et al., 2015; Popkirov, Stone, et al., 2018; Staab et al., 2017; Trinidade, Cabreira, Kaski, et al., 2023).

Balance-Land's function is to utilise visual desensitisation to rehabilitate people with visually induced dizziness. Questions raised from Phase 1 were about how to better trigger participant's symptoms and how to make Balance-Land more accessible from a user interface standpoint. Interface design was revisited according to best practice (Blair-Early & Zender, 2008), with the result being a focus on letting participants explore Balance-Land. As such, the focus became what changes could be made to allow participants to play more intuitively. For example, instead of a permanent turn button, whenever the option to turn arose, an arrow would appear in the direction of the turning.

Gamification has worked in healthcare and medical settings (Hamari et al., 2014; Pereira et al., 2014; Sardi et al., 2017), with data from Phase 1 providing preliminary evidence gamification worked for vestibular rehabilitation. This aligns with recommended rehabilitation for visually induced dizziness (Law et al., 2024; Trinidade, Cabreira, Kaski, et al., 2023), which is unsurprising as Balance-Land aimed to be a virtual representation of physical forms of rehabilitation. Feedback on the gamification elements in Phase 1 implied enjoyment would decrease over prolonged use, which would be recommended for vestibular rehabilitation (Alrwaily & Whitney, 2011; Whitney & Sparto, 2011). One of the suggestions from participants to make Balance-Land more enjoyable was additional game modes. Due to the existing play preferences of the target demographic, with casual puzzle games being highly rated on enjoyment and acceptance (Chesham et al., 2017), and the limited development time available, a similar game to the currently implemented Make Words game mode was chosen: Hangman.

Increased customisation of virtual environments to allow participants to be better able to tailor their rehabilitation is a secondary goal of Phase 2. The best theory to explain visually induced dizziness is that of visual dependence (Maire et al., 2017): people over-rely on visual cues for balance and posture. It is also known that people with visual dependence have hypersensitivity to moving or conflicting visual stimulation (Maire et al., 2017). Participants have reported increased visual sensitivity and visual stress for environments that deviate from natural statistical properties (Lukacova et al., 2023). This type of sensory sensitivity is subjective sensory sensitivity (Fischhoff et al., 1979). This means providing participants with customisation options that progressively allow more deviation from a “natural” state should allow for the best range of symptom evocation. This means focusing on high spatial frequencies and orientations (Kaping et al., 2007), such as the high-contrast bridges that had data in Phase 1 as being uncomfortable to view. Alternatively, introducing “fog” as a form of global contrast-gradient would be sufficient.

It is important to allow participants to have low-stimulation environment opportunities, due to sensory overload, which is when someone experiences perceptual distortions, continuous unchanging or intense stimuli, or sensory stimuli above desired or usual level (Scheydt et al., 2017). All three of these categories are designed to be evoked by Balance-Land. People with visually induced dizziness have reported feeling sensory overload as a result of their symptoms (Gamble, 2022) and a participant experiencing sensory overload will demotivate and make the participant stop engaging with the rehabilitation. Prior research (Doucé & Adams, 2020) has demonstrated the ability to induce sensory overload in health participants by putting them in a virtual supermarket. This means care must be taken for the virtual supermarket environment in Balance-Land, as participants will already have maladaptive behaviours towards supermarkets (Arnaudova et al., 2017), with marketplaces (Benedikt, 1870; Cordes, 1872; Westphal, 1871) and supermarkets long being identified as some of the most stimulating environments for a person with visually induced dizziness (McCabe, 1975).

Anxiety is heavily associated with visually induced dizziness (Bae et al., 2022; Kim et al., 2023; Smyth et al., 2022; Swain, 2023; Trinidade, Cabreira, Kaski, et al., 2023) with 12% of people in dizziness clinics meeting the criteria for an anxiety disorder (Murphy et al., 2021; Staibano et al., 2019) and participant comments from Phase 1 indicated unintended anxiety-provoking features were in Balance-Land. People with visually induced dizziness will develop maladaptive strategies, typically avoidant, to anxiety provoking environments (Arnaudova et al., 2017). As such, care must be taken to ensure Balance-Land does not become avoided by participants, which can be done by altering any anxiety-inducing parts of Balance-Land. However, to alter these anxiety-inducing parts of Balance-Land, they must first be identified by the participants.

In this study, we report iterative development of Balance-Land from user-centred design (Abras et al., 2004). We gather data from both clinical patients and audio-vestibular clinicians, with semi-structured interviews, which allows for rich and nuanced discussions regarding this topic (Ryan et al., 2009). Balance-Land utilises complex visual stimuli and visual flow (Popkirov, Stone, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023) to desensitise participants and habituate them to triggering stimuli. The goal with the audio-vestibular clinicians is not to rehabilitate them, as they do not have clinical symptoms of visually induced dizziness, but to focus on what can be added to Balance-Land to better facilitate rehabilitation as a whole. This is, in part, because Balance-Land will be one tool of many clinicians have available to rehabilitate people with visually induced dizziness (Hall et al., 2022; Herdman et al., 2022; Law et al., 2024; Teh et al., 2023).

The goal of Phase 2 and Phase 3 are to improve the 3 main goals of Balance-Land: rehabilitative promise, accessibility, and motivation. Investigating the sensitivities of participants allows Balance-Land to improve rehabilitative promise and accessibility, and the additional game mode (Hangman) can further motivation to play. Responsive changes to feedback is crucial and the core of the user-centred design at the heart of Balance-Land (Abras et al., 2004). Afterwards, we create design guidelines to inform others developing rehabilitation tools.

3.2 Balance-Land: Phase Two

3.2.1 Revising Balance-Land from Phase One feedback

In Phase One, some environments triggered symptoms in ways we did not expect. For example, we did not anticipate anxiety about 'falling off' the islands in Sky, which was meant to be the lowest intensity environment. We therefore converted Sky into Island, where participants would walk along wooden planks in the ocean (Figure 14A, B, & C). Further, the new menu gave users control over a range of settings to reduce or increase the visual complexity (Figure 13D), or to select one of 3 preset levels (Figure 13C) to allow incremental increases in symptom triggers (Figure 14). To increase engagement, a new game mode was added (Hangman, Figure 13B, explained further below), as were background and effect sounds.

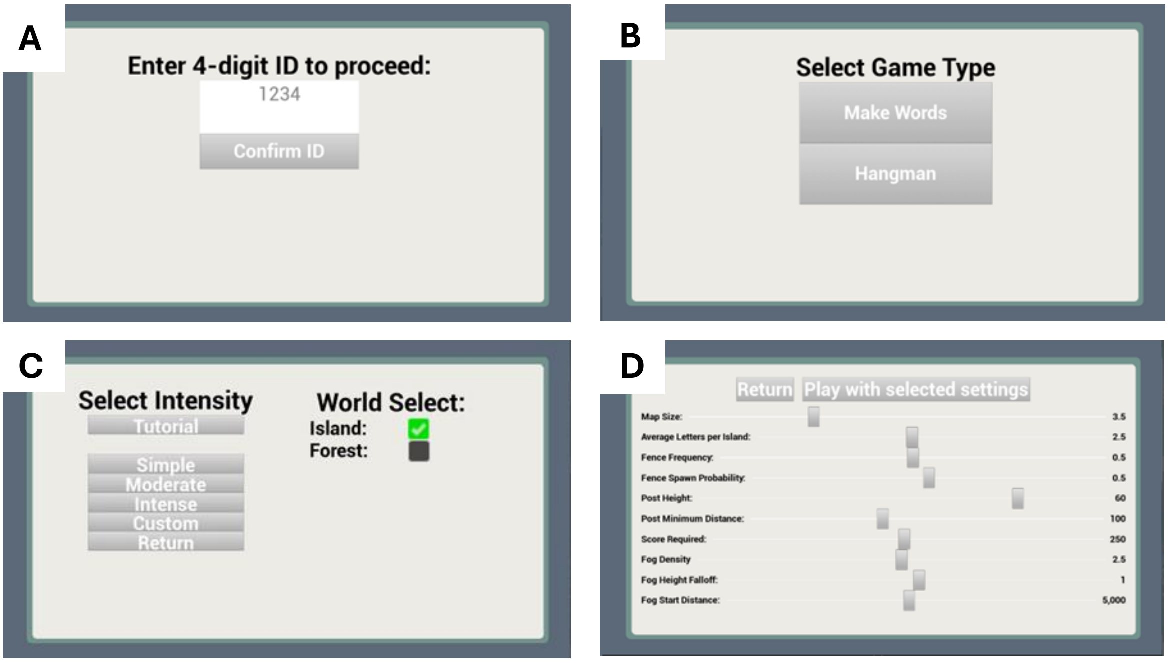
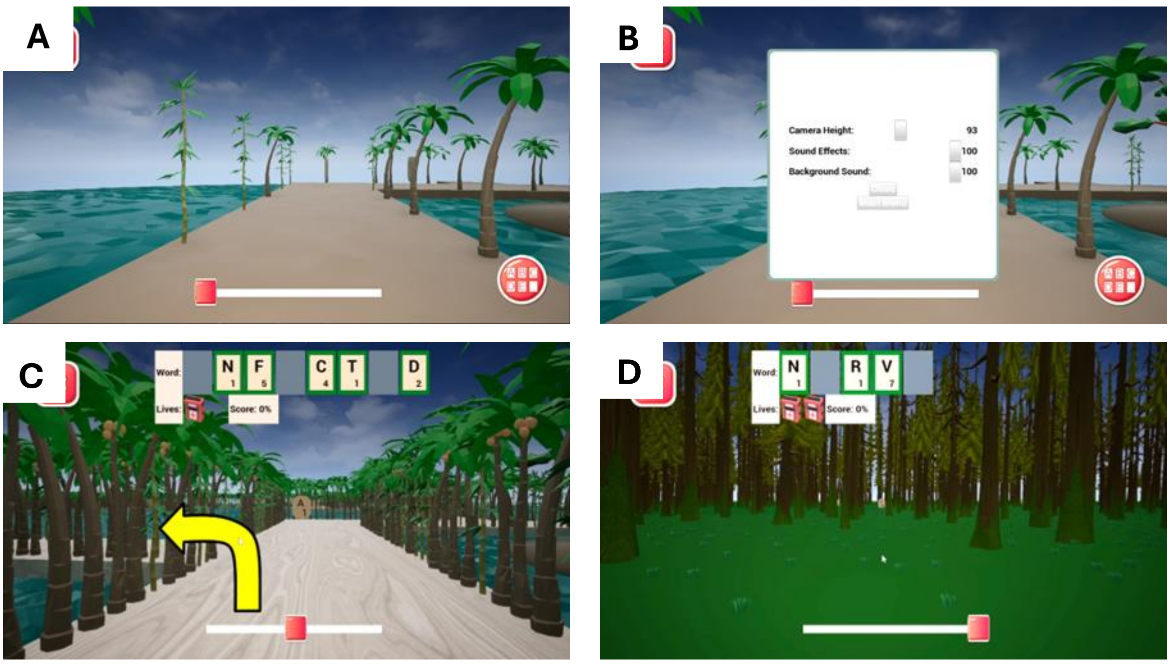


Figure 13, Screenshots of the new menu in Phase Two. 13A (top left) shows the ID screen, which progresses to 13B (top right) where participants choose the game mode. After 13C (bottom left) shows the intensity and environment select. If "Custom" is chosen, participants are shown 13D (bottom right).

The settings in Figure 13D were designed to allow participants to customise some of the visual complexity of the levels they would play. The map size would vary how many rooms would be created and linked together during map generation (see Figure 10 for a visualisation). A larger "Map size", combined with lower "Average (mean) Letters per Island (room)", would force participants to move more between gathering letter tiles, thus increasing visual flow and potentially play time. To allow for play time to remain similar between different map sizes and letter densities, whilst keeping the increased visual flow, the “Score Required” slider could change the total number of points required to successfully complete a level. The settings of “Fence Frequency”, “Fence Spawn probability”, “Post Height”, and “Post Minimum Distance” would control the proportion of fence posts versus trees spawned, the height of posts spawned, and the distance between each post or tree. Finally, the “Fog Density”, “Fog Height Falloff”, and “Fog Start Distance” sliders would control the amount of contrast on the screen, and where the contrast decrease would begin. A lower contrast would make the visuals less stimulating for participants. See Figures 14D and 14E for a comparison of no fog to high fog in the Forest.

In game controls were changed (see Figure 14) to address two primary issues identified in Phase One: participants wanted to alter the speed quickly, to alter the amount of visual flow; and the turn button was confusing. Letter spawning was jittered across the paths, rather than always direct centre, to encourage moving the mouse to click on letters. Gameplay difficulty was varied in two ways for Make Words (letter density and required score); lower letter density requires participants to explore more widely, resulting in more visual flow rehabilitation. Hangman difficulty was varied in three ways: letter density, required score, and letter removal (vowels, random letters, or all letters).



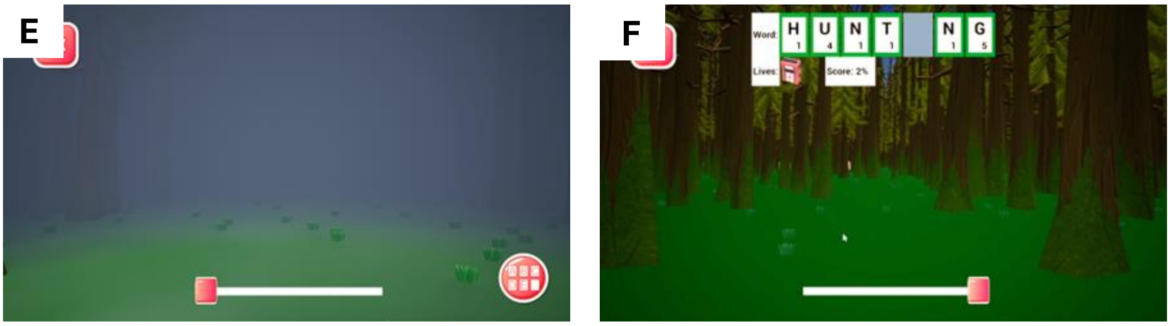


Figure 14, Screenshots of the Island and Forest environments. 14A is the simple intensity Island environment. 14B is the same environment with the settings menu open. 14C is an intense Island environment with the Hangman game mode and a turn option approaching. 14D is the Simple Forest environment with the Hangman game mode. 14E is the same environment with the maximum fog settings shown in 14D. 14F is an intense Forest environment.

3.2.2 Phase Two: System Changes and Hangman Game Mode

In Phase One, Balance-Land was created in BabylonJS (Catuhe, 2013). This created some issues in development, as being a newer engine and open source meant some features were missing, such as the ability to view the user interface without building the game. Development shifted to Unreal Engine v4.23 as it was the latest official release of Unreal Engine that supported HTML builds (Games, 2023). Unreal Engine additionally has a robust marketplace of assets that can be bought and used for development, removing the need to create custom assets. Unreal Engine uses the C++ (Josuttis, 2012) programming language instead of Typescript (Bierman et al., 2014). Unreal Engine uses Emscripten (Zakai, 2011) to convert the C++ to JavaScript, so that the code can successfully build into the HTML-accessible format.

Hangman operates by selecting a random word between 3 and 9 letters in length from the 10’000 most commonly used words in the English Language (see our repository for all words used (Github, 2024)). Letters from the chosen word were randomly removed, with the game objective being to select the letter tiles in the environment to replace the missing letters, with a finite number of guesses or “lives”. A life was lost for each letter tile selected that did not reveal a missing letter in the word (see Figure 14C, 14D, 14F, for examples). If all lives were lost, a new word was randomly selected to replace the current word and their participant’s lives were reset. Participants were given 5 lives by default, but if the easiest Hangman option was selected (vowels only) their lives were changed to 2 as 5 lives and 5 vowels meant they could not incorrectly guess a word.

The rationale behind having a potential failure state of running out of lives was because in Phase 1 participants could fixate on a point on the screen (or off-screen) and click every letter they saw, not engaging in the visuals of Balance-Land. However, in the Hangman game mode, since a failure state had been introduced, participants must actively discriminate between letters they click on, requiring engagement. The gameplay in both game modes remains similar: to move through the virtual environment and click on letters, meaning if a participant could play the Make Words mode, they could play the Hangman mode, which keeps with the goal of minimising the training participants need.

3.2.3 Phase Two: Methods

There were 10 participants recruited from a social media support group for people with PPPD in Phase Two with a mean age of 41.7 (± 17.5 years, 1 standard deviation). Participants provided feedback during a semi-structured online interview that ranged from 60-90 minutes. The goals of Phase Two were the same as Phase One: to find out if Balance-Land had, appropriate visuals for rehabilitation without excessive symptom provocation; usability by players with little video game experience; engaging gameplay for wide range of users.

The semi-structured interview was split into three sections: pre-game, gameplay, and post-game. During each interview stage participants were asked to rate their symptoms on a scale of 0 to 10, similar to relative scales of severity they would be used to answering (e.g. visual vertigo analogue scale, VVAS) (Dannenbaum et al., 2011). The pre-game section involved asking the participants about their history with VID, their difficulties with getting a diagnosis, and their experiences with VID rehabilitation. A complaint from people with VID is that they often do not feel heard, especially when trying to get diagnosed (Gamble et al., 2023): it was important to allow them to feel heard.

The gameplay section involved participants playing the simple and difficult versions of the Island and Forest environments. Participants were prompted to vocalize their experiences as they were occurring. If the participants did not comment on certain features, they were prompted on them (e.g. asking about tree sway). This allows for feedback on key changes that were made, along with any novel ideas from the participants to be analysed. Whilst coping strategies and how to minimize symptoms were not part of the semi-structured interview prompts, they were mentioned by all participants either as coping with everyday life or specifically whilst playing the game.

The post-game section involved asking the participants to provide feedback on what they liked, did not like, and where they think the game should go in the future. Participants also completed the system usability scale (SUS) (Brooke, 1996), which provides a comparison of usability across different pieces of software. A score of 80 on the SUS indicates an above-average user experience in comparison to 241 industrial usability studies, with a score of 70 being above the median (50th percentile) (Lewis & Sauro, 2018).

The interviews were recorded, transcribed and analysed by one of the authors (NG). There were three a-priori areas for directed analysis: symptoms & flexibility, accessibility & usability, enjoyment & engagement. The interviews were then analysed with conceptual content analysis (Elo & Kyngäs, 2008) with feedback being placed into one of these three areas, or not fitting into any of the three.

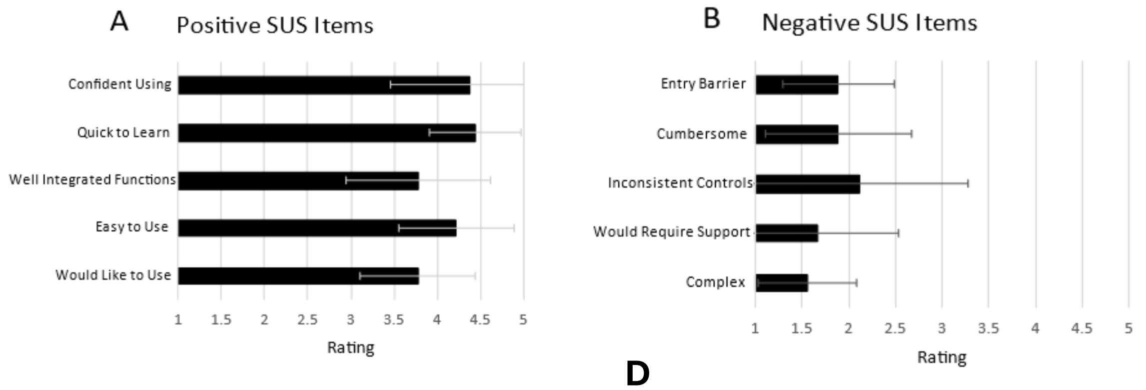
3.2.4 Phase Two: User Feedback

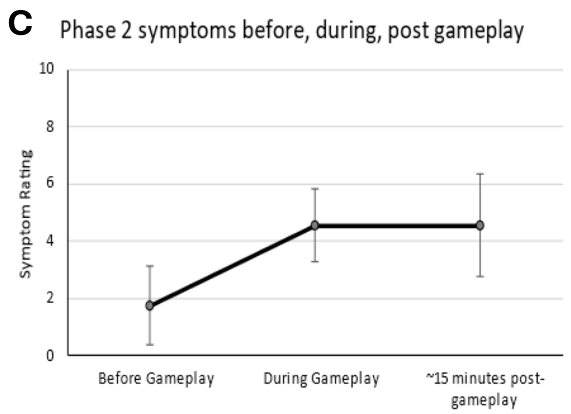
Most of the changes in Phase two aimed to improve usability. This was broadly successful: the positive aspects of the SUS were rated high (Figure 15A), while the negative aspects were rated low (Figure 15B). The game had a SUS score of 79, which corresponds to the 84th percentile relative to other pieces of software that have used the same scale (Lewis & Sauro, 2018). All participants played both environments on multiple difficulty levels, needing minimal prompting on instructions. However, 6 participants described having difficulty with at least one part of the user interface, indicating the need for further improvement. Some participants had framerate issues running the intense environments and the fog, most likely due to the laptops being used to play Balance-Land having minimal RAM, no graphics card, and having little CPU power (some participants’ laptops were over 10 years old).

The other main changes aimed to increase the range of symptom-triggering visual complexity, and to remove the anxiety associated with the Sky environment. All participants reported that symptoms were triggered by the game, and symptoms tended to increase with the intensity of the environmental levels, as intended. Importantly, symptoms again stayed in the “moderate” range, which is the ideal target for rehabilitation (Figure 15C). In Phase Two we also measured whether symptoms were transient or persisted for at least 15 minutes, and we found that they persisted (Figure 15C); ratings during and post-gameplay not significantly differ (95% CI -2.03 to 2.03), while both were higher than before gameplay (2.8, 95% CI 1.60 to 4.00, $p < 0.001$, and 2.8, 95% CI 1.27 to 4.33, $p < 0.001$, respectively). This is an important consideration for the recommended dosage.

Participants provided a range of informative feedback during the interviews; of particular interest were reported that ‘unpredictability’ or ‘randomness’ (for example in the Forest environment where paths were not as predictable as in the Island world) was particularly triggering and anxiety producing (example quotes in Figure 15D). Aspects of the game that were particular triggering varied by participant, but common themes emerged such as: horizontal screen movement, patterned floors, and swaying objects (particularly trees). All participants reported using coping strategies to reduce symptoms, for example focusing on part of the user interface or fixating on the centre of the screen. Both of these techniques would reduce motion in foveal area and reduce eye-movements. An alternate, but less popular strategy, involved focusing on the edge of the screen, looking away from the screen, or closing one’s eyes. These responses indicate that participants will self-regulate their symptom level. These responses could explain the enjoyment and nausea correlation in Phase One, whereby people that enjoy playing but experience high symptom triggers employ coping strategies to continue playing.

There was variation across participants in how much they enjoyed the game: “*It's a fun thing to do; you know it's going to help you*.” Others said that they did not particularly enjoy playing the game – some because it triggered symptoms and some because they do not enjoy playing games in general. However, all of the participants said they would play it if it was shown to reduce symptoms: “*I'm probably more likely to do something like this [than] my [vestibular] exercises, because the exercises get monotonous*”, and *“[if the physiotherapist had said] ‘we're going to have you play this game for 20 minutes each day and as a replacement [to vestibular] exercises’, I for sure would have*” (see further example quotes in Figure 15D).





D

- *I think that... the randomness of it is certainly much more triggering than [the] structure of it..., which makes it very like real life to me*
- *So .. that's anxiety inducing. It's like 'ohh where am I going and how fast and what's behind that corner? Am I going [to] bump into something?*
- *I'd use it as much as I can on a daily basis, 100% as much as possible"*
- *If somebody said this will treat you, sign me up*
- *I would play it probably. I would probably overplay it*

Figure 15, 15A shows the mean positively scored and 15B the mean negatively scored scales from the system usability scale (from Phase 2). 15C shows symptom rating of participants (N= 10) before, during, and 15 minutes post gameplay on a scale of 0 (no dizziness) to 10 (worst possible dizziness). Error bars are ± standard deviation. N = 10. 15D provides some example quotes from the interviews.

3.3 Balance-Land: Phase Three

3.3.1 Phase Three: Revising Balance-Land from Phase Two feedback

To have better control over the visual scenery and create a more robust suite of virtual environments, the procedurally generated world was changed to a fixed world with different sections for the different environments (Figure 16). Participant feedback so far had not indicated any clear advantage for the procedural generation. The Island environment was changed to a Desert environment to completely remove falling-related anxiety and reduce visual complexity even further. The Forest environment was changed to have clearer paths with customizable tree options for visual complexity. A Supermarket environment was added and had a range of shelf heights, product sizes, product colours, and alternate floor designs. The option to limit contrast and visibility via fog was removed as it decreased performance, with new options for head bob and head roll being added. New assets that were less polygon intensive were chosen for existing assets. Framerate was capped at 30 FPS.

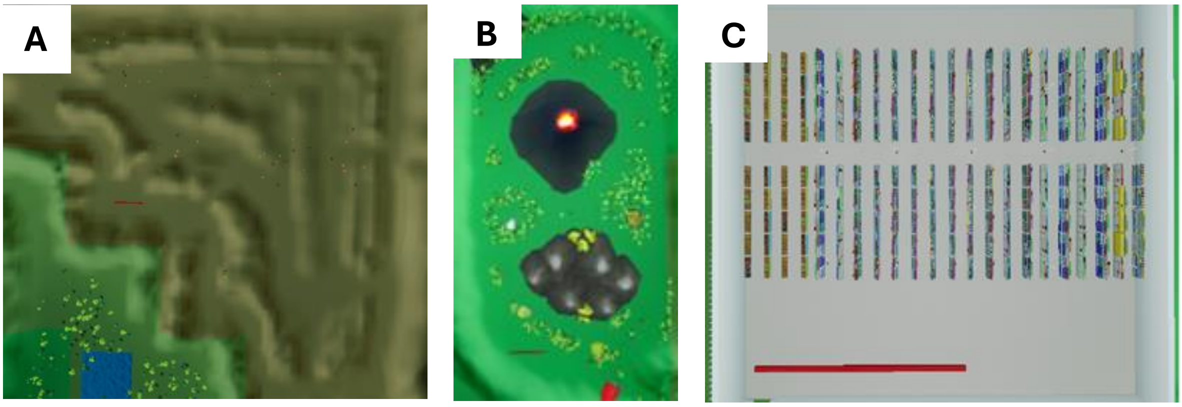


Figure 16, 16A is the Desert environment. 16B is the Park environment. 16C is the Supermarket environment. The red bar is the same absolute size in each image to provide scale.

Participants selected the environment and game mode to play (Figure 17A), with an additional game mode, shopping, available in the Supermarket, where participants had to discriminate between items on shelves according to a randomly generated list of desirable items. Selecting an item was identical to selecting a letter: clicking on the item. The shopping items were outlined in orange and the outline was visible through the shelves. Each item had at least one other item with a similar silhouette. Forcing participant discrimination should aid with the identified coping strategies, since participants must look at different areas of the screen to see the shopping items. This mode was added due to comments from participants in Phase One e.g. "*alter the supermarket game so it replicates a shopping experience*". This was in line with other changes made to make the virtual environments more similar to their real-world counterparts, based on prior feedback.

The control changes from Phases One to Two appeared to be functional and were not substantially altered. The user interface of the Hangman game mode (renamed to Find a Word) was improved due to clarity concerns. Guessed letters were tracked in the screen corner, with green for a successful guess and red for an unsuccessful guess (Figure 17B). To alleviate frustration about failing to guess a word, the word was shown in the top right after all lives were lost or it was successfully guessed.

There were no changes to Make a Word (rename from Make Words, Figure 17C). Rotation buttons were added to the shopping game mode, to allow participants to rotate and fully face a shelf (Figure 17D).

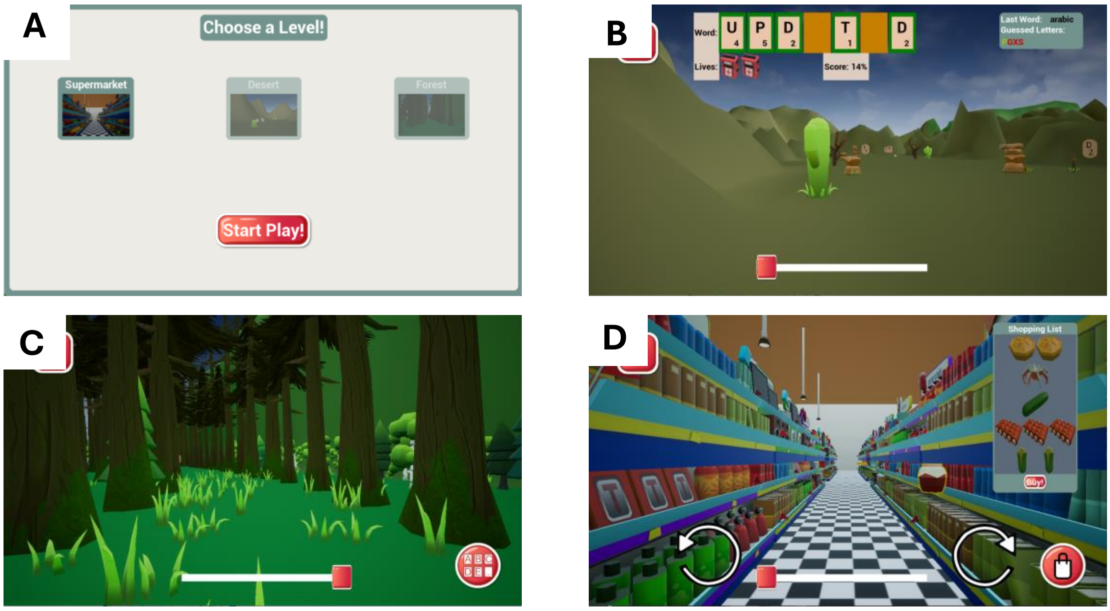


Figure 17, 17A shows the new environment select menu. 17B shows the Desert environment with the Find a Word interface alterations. 17C shows the Park environment with Make a Word game mode. 17D shows the Supermarket environment with the patterned floor and Shop game mode.

3.3.2 Phase Three: User test description and results

The primary way rehabilitation is recommended to patients is via Audio-vestibular clinicians. As such, data from clinicians beyond the research team collaborators was required for the next phase of development. Audio-vestibular clinicians based in the UK (n=6) were recruited from clinicians that had expressed interest in Balance-Land via a conference, or from colleagues of clinicians that had expressed interest in Balance-Land. Demographic information or clinical experience were not recorded for the clinicians, with the only inclusion criteria being currently employed as an audio-vestibular clinician and treating patients with visually induced dizziness.

The clinicians were asked to play Balance-Land for 15 to 30 minutes then answer a structured interview, with questions provided prior to playing Balance-Land. The list of questions provided to clinicians was created with two sections: mandatory questions and optional questions. The mandatory questions focused using Balance-

Land and how best to set Balance-Land up for a randomised control trial. The optional questions focused on how to improve specific aspects of the game e.g. “Do you think there should be any changes to the controls to make the game more accessible to patients?“ (see Appendix 2 for a full question list). Clinicians were offered the opportunity for a one-on-one online interview or to e-mail back written responses to the interview questions.

All of the clinicians said that they would recommend the game to patients if there was evidence of improvement in symptoms. Interestingly, most (5) said that they would prioritize a reduction in anxiety over dizziness symptoms. Clinicians suggested that we measure improvements in dizziness symptoms via self-report questionnaires (e.g. vestibular rehabilitation benefit questionnaire) and posturography. Being web-based, posturography would be difficult to measure for participants, however self-report questionnaires being added to Balance-Land could be easily implemented. Suggestions for gameplay changes to improve rehabilitation included: increased complexity to challenge patients, new virtual environments, and moving objects on the screen.

Clinicians thought the best stage to fit the game into their treatment pipeline would be during their second meeting, with the initial meeting explaining VID to the patient and going over how it affects them. Balance-Land would only be recommended to patients if clinicians thought they were technologically adept enough to play it unsupervised. Even though the game could be utilized during a waiting list, there were concerns over whether patients would know what environment and visual difficulties to target. The primary concern was that patients would set the starting visual intensity too high.

3.4 Discussion

We report on the development of Balance-Land, a new web-based rehabilitation game for visually induced dizziness (VID). The game was developed during three phases of iterative feedback with people with VID and clinicians. Our development challenge was to create a web-based VID rehabilitation program that delivered visual stimulation at a tolerable level, packaged in an engaging format that individuals with lower video game experience could play across a range of devices. Unlike off-the-shelf solutions such as the Wii-fit (Jones & Thiruvathukal, 2012), we wanted to provide flexibility over intensity of therapeutic stimulation and allow patients access to virtual environments that they fear in the real world (e.g. supermarkets). We also de-coupled the game-play controls from the therapeutic stimulation by using simple puzzle and collection games to ensure wide accessibility even to those with no previous video game experience. We discuss the results of our development process as it relates to rehabilitation, useability and engagement, and present guidelines for developers in the future looking to design rehabilitation tools for VID and related conditions.

3.4.1 Rehabilitation

Feedback from people with VID confirmed that Balance-Land achieved our aim of triggering symptoms at moderate levels. A certain degree of symptom provocation is hypothesized to be needed for visual desensitization (Popkirov, Stone, et al., 2018; Shepard et al., 1990; Yardley & Luxon, 1994), however, this should be at a level that is tolerable to participants, and ideally tailored to their needs. Central to the design of Balance-Land was flexibility over different levels of therapeutic intensity, so that patients could start with lower intensity stimulation and progress to higher stimulation as their condition improves. Off-the-shelf options such as the Wii-fit, which have been previously tested (Shih et al., 2010; Verdecchia et al., 2014), do not offer such options for therapeutic flexibility and are therefore not suitable for patients who may be triggered by even gentle stimulation.

In Balance-Land, we sought to create a tool that was inspired by patient and clinician experiences of VID and captured the key environmental triggers that are characteristic of the condition (e.g. high contrast, complex patterns, high speed motion). As well as visual exposure to these environments, we predicted that virtual exposure to feared environments might aid in confidence-building and anxiety reduction. This was reflected in qualitative feedback from some of the participants with VID, "*I find in real life I can't walk comfortably over a bridge. This game got me to feel better about it".* In the future, we hope to build on this and introduce new triggers that were mentioned during this development process, including more passive motion in the world (people and vehicles moving around) and more realistic environments. Clinicians in Phase Three supported these future directions, noting that more realistic graphics and progression options for patients would be their preference.

An unintended outcome during user-testing was the prevalence of coping strategies employed by users with VID to reduce the number of symptoms triggered. The main identified strategies were fixation on a UI element or on the centre of the screen, with some users occasionally closing their eyes. However, our data suggest that despite these coping strategies, symptoms were still triggered. Future user testing could employ eye tracking to objectively test the degree to which participants employ fixation-based copy strategies. Although some coping strategies are acceptable and allow users to keep stimulation within a tolerable range, it would be interesting to explore if this hinders rehabilitation progress, and if so, if additional gameplay elements are needed to prevent them (e.g. to encourage more eye movements across the screen).

Guidelines for VID rehabilitation design:

- Participants should be constrained to play low-level stimulation environments before progressing to more intense levels, with graded exposure to each type of symptom trigger, so they can determine which types they are most susceptible to.
- Where virtual environments incorporate many of these different types of symptom triggers, some should be optional, to allow participants to maintain symptoms at a tolerable level (e.g.: camera roll was optional on the Island environment to mimic waves on the sea, fog was optional as a way of reducing visual contrast and visual flow).
- Virtual environments that more closely resemble real-world environments have more reports of anxiety reduction and should be prioritized.
- Participants find motion along fixed paths more unpredictable than the game designer; for example, they do not know it is impossible to fall off a path. This implied possibility is anxiety-producing and should be avoided.
- Participants try to minimize symptom triggers with coping strategies, which leads to a desire for more triggering environments. This can be achieved by putting in more symptom triggers, or alternatively, should be achievable through gameplay alterations that force retinal movement. Coping strategies

cannot be fully removed, with in-game education to participants about their symptoms a likely better solution than making changes that negatively impact game experience.

3.4.2 Usability

A key user-design objective was that Balance-Land was accessible to a wide range of people, even those with no video game experience, and across a range of devices, including those with low specifications. This was one of the greatest challenges during development, as many of the devices' participants were using were over a decade old, severely constricting the polygon and texture budgets. Furthermore, users with VID reported that dropped frames below 30 FPS tended to exacerbate symptoms. However, by the end of Phase 3 development these issues had mostly been resolved with the move to Unreal Engine and low-poly graphic solutions. An advantage of Balance-Land is that it does not require expensive hardware, like a specific game console (e.g. Wii) or virtual reality headset and can be played on even quite an antiquated laptop or tablet. Having utilized low-poly graphics to accommodate for user equipment, Balance-Land was still able to trigger symptoms and reduce anxiety. We did not scale graphics to the user's capability due to needing the same visuals for all participants. However, participant comments suggest graphics that more closely represent the real-world would be more effective at rehabilitating, which appears to be supported by participants reporting more symptom triggers in real-world environments than virtual ones, making graphics scaling a potential alternate source of increasing rehabilitative efficacy.

Another key challenge was designing game controls for users unfamiliar with playing video games. Clear instructions were essential, and we have subsequently developed a suite of video and in-game tutorials to help users learn how to play the game independently. Overall, participants rated the game highly on the System Useability Scale, with a score of 79, placing it at the 84th percentile relative to other software (Lewis & Sauro, 2018). Including clear feedback and signalling within the game – both visual and auditory reinforcement - was reported helpful by users.

Guidelines for VID rehabilitation design - usability:

- Typical users with VID may have very little-to-no game experience. This means avoiding complex or reaction-time based controls, and anything in the game should have immediate feedback and a clear purpose.
- Typical users with VID may have old or low-spec hardware, and thus processing requirements need to be minimized (e.g. using low-polygon graphics).

3.4.3 Engagement

Feedback from users with VID suggested that they were generally more concerned with effective rehabilitation than they were with enjoying the game element of Balance-Land. However, some participants did report enjoying the game and appreciated the principle of having something to do while they receive visual desensitization therapy. Other participants, often those with no video game experience, did not particularly appreciate the video game element but still said that they would play Balance-land if it was shown to aid their recovery. As such, the best way to ensure participant engagement might be to have methods of feeding back to participants about their rehabilitation progress. Some participants liked the idea of taking daily or weekly symptom ratings and then receiving feedback on this, for example in the form of an interactive graph. Such feedback could also be shared with clinicians, who could track progress and recommend any changes to rehabilitation schedule. Furthermore, participants with VID liked gamification ideas that could foster community ties, such as communal scoreboards, challenge targets, and daily streaks.

Participants with VID also suggested including a wider range of game modes to increase engagement and enjoyment, such as sudoku and crosswords. Gameplay durations of around 5-10 minutes per day were suggested by both people with VID and clinicians. This would need to be repeated a few times a day in order to gain rehabilitative benefit (Alrwaily & Whitney, 2011; Whitney & Sparto, 2011; Whitney et al., 2020).

Guidelines for VID rehabilitation design - engagement:

- Gameplay enjoyment is secondary to rehabilitative benefit but must be engaging enough to retain participants until rehabilitative benefit can be shown; low-polygon graphics and basic gameplay was sufficient to provide a moderately enjoyable game experience that patients reported as preferable to current rehabilitation exercises.

- Participants report high scores, progressing through difficulty levels, and community ties as effective forms of motivating engagement.
- Participants enjoy progressing through levels but will employ coping strategies to do so, giving a false sense of progression. Tying symptom triggers to the gameplay of higher difficulties can ensure participants still receive rehabilitative benefit whilst progressing.
- Participants want a variety of gameplay options but do not want locked-in time commitment. Keeping the gameplay loop close to 5-to-10 minutes appears ideal.

3.5 Conclusions and future work

Balance-Land has all the requisite features to effectively rehabilitate VID but requires a larger scale test to determine its effectiveness. Through three phases of iterative feedback with people with VID and clinicians we have built an evidence bank that enables us to offer guidelines about how best to design a game for VID rehabilitation. The usability guidelines are similar to existing design guidelines for novice game users, however there are important differences concerning the interaction of game play and triggering symptoms. Participants in the current study were highly motivated, and participants being given this as rehabilitation with less motivation may not respond in the same manner, highlighting the need for gamification elements. A feasibility study with more ecological validity, testing how participants would utilize the game in an everyday setting, is an important next step. Regardless, this research shows that gamification of vestibular rehabilitation is possible with Balance-Land.

4 Feasibility of gamified visual desensitisation for visually-induced dizziness

4.1 Abstract

Visually-induced dizziness (visual vertigo) is a core symptom of Persistent Perceptual Postural Dizziness (PPPD) and occurs in other conditions and general populations. It is difficult to treat and lacks new treatments and research. We incorporated the existing rehabilitation approach of visual desensitisation into an online game environment to enhance control over visual motion and complexity. We report a mixed-methods feasibility trial assessing: Usage and adherence; rehabilitation potential; system usability and enjoyment; relationship with daily dizziness. Participants played online with (intervention, N = 37) or without (control, N = 39) the visual desensitisation component for up to 5-10 minutes, twice daily for 6 weeks. Dropout was 45%. In the intervention group, n=17 played for the recommended time while N=20 played less. Decreases in visual vertigo symptoms, anxiety and depression correlated with playtime for the intervention but not control. System usability was high. Daily symptoms predicted playtime. Qualitative responses broadly supported the gamified approach. The data suggest gamified visual desensitisation is accessible, acceptable and, if adherence challenges can be overcome, could become a useful addition to rehabilitation schedules for visually-induced dizziness and associated anxiety. Further trials are needed.

4.2 Introduction

Visually-induced dizziness, or ‘visual vertigo’, is a debilitating symptom occurring across several disorders and conditions, such as Migraine and Meniere’s Disease, or after Traumatic Brain Injury, and it is a core feature of Persistent Postural Perceptual Dizziness (PPPD), the leading cause of chronic, functional dizziness (Staab et al., 2017). It also exists on a spectrum in the healthy population (Powell, Derry-Sumner, Rajenderkumar, et al., 2020). Patients experience symptoms of dizziness, unsteadiness and non-spinning vertigo that are triggered or exacerbated by visual motion and complex visual environments (Staab et al., 2017). Such vulnerability to visual environments tends to be persistent and very difficult to treat. Anxiety is a common correlate, with patients often developing fear of everyday situations that may trigger symptoms (Bronstein, 1995).

Current treatment involves daily vestibular rehabilitation exercises and visual desensitisation, aiming to recalibrate sensory integration and reduce hyper-reactivity to visual stimulation (Popkirov, Stone, et al., 2018). For example, watching recorded optokinetic stimuli (moving bars or light spots) for up to 45 minutes daily for 8 weeks was found to improve dizziness, posture and gait (Pavlou et al., 2004; Yardley et al., 1992). Clinically, people with visually-induced dizziness are often advised to view videos with radial optic flow or with moving patterned stimuli with the aim to desensitise to these visual inputs relative to information from their vestibular system (Pavlou et al., 2013). Given the common association with anxiety, treatment can also include psychological therapies (e.g. cognitive behavioural therapy(Herdman et al., 2022)) and pharmacological agents (e.g. selective serotonin re-uptake inhibitors) to break the perpetuating anxiety-dizziness cycle and help patients cope with symptoms in everyday life (Popkirov, Stone, et al., 2018).

However treatment success is highly variable, and a major challenge for all chronic dizziness rehabilitation is adherence (Pavlou et al., 2013) – therapy provokes symptoms and is unengaging (Gamble et al., 2023). A second limitation is insufficient flexibility for individual patients, who show a wide range of symptom severities and situational triggers for dizziness and anxiety (Pavlou et al., 2013). Too much stimulation too soon inevitably results in discontinuation (Whitney et al., 2020).

Gamification has helped rehabilitation in other domains, including chronic disease management, physical activity, nutrition, mental health, and hygiene (Sardi et al., 2017). However, online videos or games containing optic flow potentially suitable for visual desensitisation tend to contain high levels of motion and visual complexity that are too intense for patients with visually-induced dizziness. We therefore developed a new online rehabilitation game (‘*Balance-Land*’) as a puzzle game within an environment where the optic flow and scene complexity can be graded and controlled separately from puzzle difficulty (Figure 18). Participants are able to choose the environment (Desert, Park, or Supermarket) they feel appropriate for their symptoms, and also adjust motion speed to scale symptom provocation. We have developed the tool through iterative consultation with patients and clinicians (Goodwin et al., 2023), to ensure that it is user-focused and can be tailored to individual patient needs. Balance-Land is free to use and can be accessed and viewed here: https://cudizzylab.org/playbalanceland/ . The aim is not to replace other kinds of rehabilitation therapy, but rather to provide an additional pragmatic home-based option for flexible multi-faceted treatment for the range of patients experiencing visually-induced dizziness.

In this paper, we present the results of a semi-randomised mixed-methods 6-week feasibility trial of Balance-Land in which participants played the puzzle games with (intervention group) or without (control group) moving through the virtual environments (the visual desensitisation component). The goals of the feasibility trial were to assess:

1. Dropout and adherence: would participants be willing to use the game twice daily for 5-10 minutes for 6 weeks?
2. Rehabilitation potential: primary outcome of self-reported visually-induced dizziness symptoms (the visual vertigo analogue scale, VVAS) before and after using the game for 6 weeks and whether this depended on playtime, and secondary outcomes of anxiety, depression and other dizziness questionnaires.
3. System Usability and enjoyment: participants reported useability and previous digital experience, and game data was recorded to assess if all controls and game areas were utilised. They also rated enjoyment.
4. Daily symptoms: participants reported how dizzy or unwell they felt at each game session, so we could assess if this predicted usage.

Figure 18, Images from Balance-Land. Players move through virtual environments collecting letters for word games or collecting items from a shopping list. Different zones provide different intensities of visual motion stimulation: the Desert zone ((top left) is low contrast and spatial frequency, with a limited colour palette and few objects; the Park zone (top right) steps up these characteristics, with high contrast tree trunks; the Supermarket zone (bottom) has high contrasts and spatial frequencies, with many cluttered objects (supermarkets are a major dizziness trigger for patients (Dannenbaum et al., 2011; Yagi et al., 2019)).

4.3 Methods

4.3.1 Balance-Land – description and development

Players move through virtual environments collecting letters for word games or collecting items from a shopping list. Different zones (Figure 18) provide different intensities of optokinetic stimulation: the Desert zone is low contrast and spatial frequency, with a limited colour palette and few objects; the Park zone steps up these characteristics, with tree trunks and bushes; the Supermarket zone is high contrast and spatial frequency, brightly coloured, with many objects (chosen to simulate a common situation where patients have difficulties (Dannenbaum et al., 2011; Yagi et al., 2019). Within each zone, players can change the movement speed and steadiness, choose to enter more visually complex areas, and choose puzzle settings that provide more or fewer breaks from visual stimulation.

Word games and shopping lists were selected as accessible to a wide range of users without requiring experience with computer game controls (Salmon et al., 2017). Puzzle games also crucially allow for the gameplay difficulty (i.e. puzzles) to be decoupled from the difficulty of the rehabilitation (e.g. speed and complexity of optokinetic stimulation). A web-based platform was used to ensure access from different types of devices, as well as enabling gameplay information to be recorded.

Balance-Land was developed over three rounds of iterative feedback, via questionnaires and interviews, with patients and clinicians(Goodwin et al., 2023). In total, 21 people with PPPD and visually-induced dizziness symptoms and 6 clinicians helped to design and optimise all aspects of the game. This development process established the need for Balance-Land, helped to ensure user-accessibility and enjoyment, and provided insight into how to titrate rehabilitation intensity.

4.3.2 Design

The study was designed with two parallel groups, pseudo-randomised to match groups on key characteristics, with an assessment before (Time 1) and after (Time 2) six weeks of access to Balance-Land or a control version of the game without optic flow. Participants were additionally invited to a structured qualitative interview after Time 2. All qualitative data was analysed with conceptual content analysis (Elo & Kyngäs, 2008).

4.3.3 Setting and Participants

All methods were carried out in accordance with relevant guidelines and regulations. Experimental protocols were approved by the Ethical Committee of the School of Psychology, Cardiff University. Written informed consent was obtained from all participants.

Participants took part online and were able to play the game at home on their own laptop, computer, or tablet. Adults (aged 18 or over) were recruited online through VEDA (https://vestibular.org), the Meniere’s Society (https://www.menieres.org.uk), and social media. Volunteers were initially screened with the Visual Vertigo Analogue scale (VVAS) in which nine environments and triggers (commonly associated with visually-induced dizziness) are rated from 0-10 for the degree they evoke dizziness (Dannenbaum et al., 2011). Volunteers were invited to take part if their severity score exceeded 40 (moderate (Frank et al., 2022); see figure 19 for a recruitment pipeline). Participants had to be able to read and understand English but were not excluded on other criteria and any person with an internet connection was eligible to join.

We based recruitment on VVAS severity scores rather than current diagnoses for three reasons: visually-induced dizziness occurs across more than one condition; visual desensitisation is aimed at the experience of visually-induced dizziness, rather than being expected to treat all aspects of a condition, such as PPPD; diagnosis for dizziness-related conditions is notoriously difficult and often incorrect (high levels of misdiagnosis have been reported across Europe, USA, and China (Jin et al., 2012; Thomson, 2017; To-Alemanji et al., 2016; Van Leeuwen & Van Der Zaag-loonen, 2015), concurring with our clinical experience).

4.3.4 Randomisation

Participants were pseudo-randomised in batches in order to match the intervention and control groups on three factors: VVAS severity score, age, and duration of symptoms, prioritised in that order (see table 1 for participant information), and in order that volunteers were not kept waiting more than a week to join the study. In other words, the first pair were randomly allocated to different groups, and then for all possible permutations of allocation for the rest of the batch, the difference in mean VVAS score between the groups was calculated and the permutation selected that minimised this difference (using Excel for Microsoft 365 v2406). If more than one permutation offered acceptable matching (1 point difference or less), then difference in mean age was minimised. If more than one permutation kept mean age difference below 1 year, then difference in mean illness duration was also minimised. The researcher was blind to all other participant information at allocation. After allocation, all interaction with the data was via participant ID codes that did not reveal the group. This also allowed the researcher to provide technical support and to perform exit interviews without knowing the group (although some participants revealed their group through their comments).

4.3.5 Procedure

Both groups were recommended to play for (no more than) 5-10 minutes twice daily (symptoms allowing) for six weeks. Participants were asked not to make any adjustments to any current treatment plan or any other activities relevant to their symptoms, but to simply play the game in addition. Participants were told that Balance-Land might trigger symptoms, and to pause, take a break, or stop playing, depending on the severity of the symptoms. The instructions were '"The goal is to evoke **MILD** symptoms. If you are experiencing more than this, please lower the speed, go to a simpler environment, or take a break."

4.3.6 Intervention group

Participants in the intervention group played Balance-Land. During each game session they could freely choose between playing three virtual environments: Desert, Park, and Supermarket (see figure 18). There were three possible game modes: Find a word; Make a word; and Shop (only available in the Supermarket). Participants were not restricted in what they could access, but they were advised to keep symptom triggering at a comfortable level rather than over-stimulate (going to the Supermarket too soon, for example). Participants were given a series of short (<2 minutes) video tutorials that covered how to play the game and the options available. These tutorials remained available via a link in-game.

4.3.7 Control group

Participants in the control condition played a modified version of Balance-Land, with no virtual environments to move within, thus eliminating the optic flow aspects of gameplay. They could play two game modes: Find a word; and Make a word, but letters were provided and did not need to be found within the virtual environments. Participants were given a series of short (<2 minutes) video tutorials that covered how to play the games (which remained available via a link in-game).

4.3.8 Feasibility outcomes and planned analyses

Dropout and adherence: We offered each participant who stopped playing the game during the trial (no gameplay for a week), or who never played a single session, the opportunity to provide a reason. We measured the active time played by each participant, defined using any input 30s or less from another input (to remove instances where participants left the game running whilst not being used, for example if they were taking a break or in order to carry on from the same stage the next day).

Rehabilitation effect: We used VVAS score (outlined above) as the primary outcome measure, assessing the change between time 1 and time 2 and dependency on total game playtime (assessed with ANOVA and correlation). Secondary outcome measures were also included: Dizziness Handicap Inventory (DHI (Jacobson & Newman, 1990)), the Niigata PPPD Questionnaire (NPQ (Yagi et al., 2019)), and the Hospital Anxiety and Depression Scale (HADS (Zigmond & Snaith, 1983)). All surveys were delivered in Qualtrics (Qualtrics, 2005). At Time 2 participants were able to provide open-ended answers about their experiences, as well as sign up for a post-trial interview.

Digital accessibility and usability: to assess usability participants completed the System Usability Scale (SUS (Brooke, 1996)) at Time 2 only. As secondary outcomes, we used gameplay data to assess whether participants accessed all virtual environments and controls, and asked how quickly they learnt the controls. We particularly focussed on participants with lower digital experience (Participants reported level of digital experience at time 1 only: every day, ~2x a week, <1 a week).

Enjoyment: participants rated their enjoyment of the game out of 10 at time 2 and provided qualitative feedback (if they participated in the interview).

Daily symptom diary: We used a simple brief rating scale to assess daily symptoms so that we could assess whether this predicted how much participants engaged with the game. For each session, participants were asked: “Before playing Balance-Land today, how severe are/were your symptoms?”; and “After playing Balance-Land today, how severe are/were your symptoms?”. Participants selected one of six faces that progressively changed from smiling to frowning and crying. We also asked if they had performed other vestibular rehabilitation (yes/no).

Statistical Methods: We used descriptive statistics, 95% CI, correlation and ANOVA (see Appendix 3 supplementary Figure S1 for ANOVA results), using Jamovi (version 2.3.28)(Jamovi, 2024) and SPSS (version 27)(*IBM SPSS Statistics for Windows*, 2020). We do not give p values in order not to overemphasise significance in a feasibility study. Figures were plotted using Screencaps, Excel and Powerpoint for Microsoft 365 v2406, Matlab R2023A (https://uk.mathworks.com/products/new_products/release2023a.html)

4.4 Results

4.4.1 Enrolment, dropout and adherence.

Numbers of participants recruited and completing are given in Figure 19. The enrolment rate was 35% and the retention rate was 55%. Participants were recruited globally, with the majority from the USA, UK, and Canada. The most common reported current diagnoses were PPPD (37), vestibular migraine (31), and Meniere's Disease (10) (no significant difference between groups; numbers given are for participants completing the study; see Appendix 3 Supplementary Table S1 for more information). These were non-exclusive and many other comorbid conditions were reported. Note that diagnosis for dizziness is challenging and known to be often incorrect (with over-diagnosis of Meniere's Disease, for example: (Thomson, 2017; To-Alemanji et al., 2016)). Hence, we took a symptom-based approach, matching groups for VVAS severity rather than reported diagnoses. The proportion with PPPD was much higher in those who enrolled compared to those invited (meeting inclusion criteria) who did not enrol, but there were no other major differences in characteristics measured at screening (see Appendix 3 Supplementary Table S2). Compared to cohorts in the literature with PPPD, vestibular migraine and Meniere's Disease (Axer et al., 2020; Bruderer et al., 2017; Chari et al., 2021; Kim et al., 2023; Kirby & Yardley, 2009; Söderman et al., 2002; Zhang et al., 2022), our enrolled cohort had similar mean age, higher female:male ratio, and higher scores on DHI and HADS (which is to be expected given these correlate with VVAS, where we had an inclusion criterion of >40; see Appendix 3 Supplementary Table S3).

There was no significant difference in dropout rates between intervention and control groups (44% vs 46%, $x^2(1,61) = 0.004$). Most participants withdrawing from the study did not give a reason. Of those that did, the reasons were: other health issues (6); technical issues (3); time commitment for study too large (2); evoked symptoms too severe (2); difficult daily life (1); game too difficult (1); no effect noticed (1). There was no difference in initial VVAS scores for those that completed vs those that did not (72 vs 70, $t(136)=.94$). Neither was there any difference in reported digital experience ($x^2(4,137) = 1.5$); 64 of 113 (57%) everyday computer users completed, while 13 of 25 (52%) less frequent users completed.

Of the participants who completed the study, 17 adhered to the recommendation of playing, on average, 5-10 minutes twice daily for 6 weeks (7 hours or more in total over 42 days). Twenty participants played less than this (see table 1 for comparison between these groups). In order to answer the remaining feasibility objectives, it is therefore essential to take playtime into account when assessing the study results (we present correlations with playtime below, and in Appendix 3 we provide separate results for those adhering to recommendations). Note that any analysis approach utilising playtime breaks the randomisation, because amount of playtime was self-selected by participants.

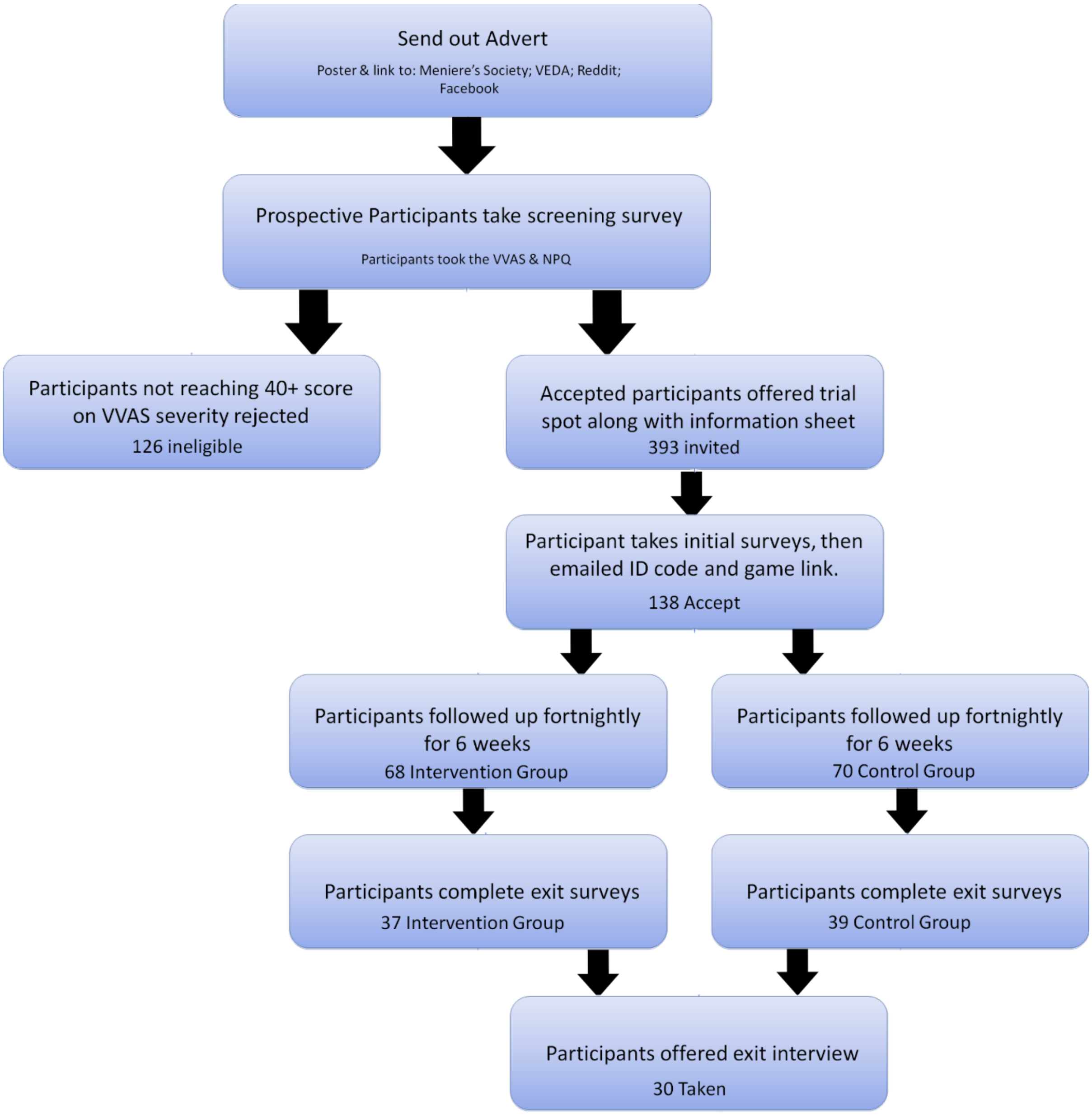


Figure 19, Recruitment and retention pipeline for participants. The enrolment rate was 35% and the retention rate was 55%.

Table 1, Participant information prior to study (at time 1) for all those that completed time 1 assessment (first two columns) and for those that completed time 2, six weeks later (right hand four columns; also comparing those that adhered to recommended playtime with those that did not). Means and SD are given, except where data are categorical. Pseudo randomisation aimed to minimise differences in VVAS severity, age and symptom duration across groups (bold rows).

	Participants at Time 1 (scores are time 1)			Participants at Time 2 (scores are from time 1)			
	Control N = 70	Intervention N = 68		Control N = 39	Intervention = 37	Low Playtime N = 20	Recommended N = 17
VVAS Severity	**70.2 (±16.4)**	**71.4 (±15.7)**		**72.6 (±14.9)**	**73.2 (±16.4)**	**71.0 (±18.6)**	**75.8 (±13.3)**
Symptoms Duration (months)	**84.5 (±108.6)**	**89.8 (±114.9)**		**99.0 (±134.8)**	**94.7 (±123.4)**	**85.4 (±108.0)**	**105.7 (±142.1)**
Age (years)	**51.3 (±14.4)**	**51.6 (±14.1)**		**51.9 (±14.7)**	**52.8 (±14.3)**	**49.5 (±17.0)**	**56.9 (±8.8)**
Gender (female; male; other)	56; 12; 1	59; 8; 1		33; 5; 1	33; 3; 1	16; 3; 1	17; 0; 0
DHI	66.7 (±16.6)	66.4 (±16.0)		66.8 (±16.1)	69.0 (±15.0)	69.7 (±15.8)	68.2 (±14.6)
NPQ	36.7 (±12.2)	34.5 (±11.7)		35.5 (±10.2)	35.2 (±11.5)	36.3 (±10.6)	33.8 (±12.8)
HADS Anxiety	10.3 (±4.2)	10.6 (±4.1)		10.4 (±4.0)	10.7 (±3.7)	12.5 (±3.4)	8.7 (±3.1)
HADS Depression	8.8 (±4.1)	8.9 (±4.0)		8.8 (±4.3)	9.6 (±4.4)	10.9 (±4.8)	8.2 (±3.5)
Computer Use	56; 7; 6	56; 10; 2		32; 5; 2	31; 5; 1	17; 3; 0	14; 2; 1

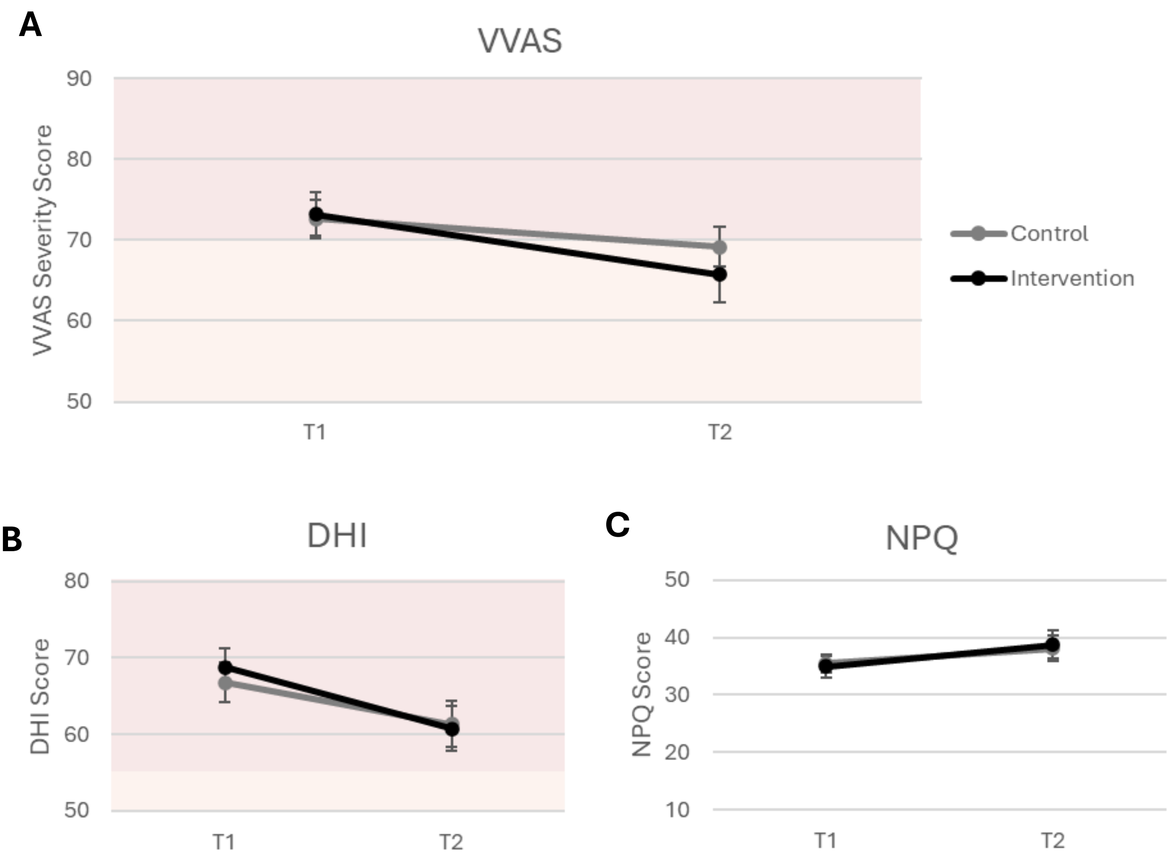
(Everyday; ~2x a week; <1 a week)							

4.4.2 Rehabilitation effects

The primary outcome measure was VVAS severity scores. These reduced from a mean of 73.2 at time 1 to 65.8 at time 2 for the intervention group (Figure 20A), with a smaller numerical reduction in the control group (72.6 to 69.1). More importantly, there was a clear correlation of this reduction with time spent playing the intervention game, but not for time spent playing the control condition (Figure 21A, $r(37) = -0.43$, $p < 0.008$, 95% CI [-0.66,-0.12], see also Appendix 3 supplementary Figure S1 for mean results for participants adhering to recommended playtime).

Our secondary dizziness and mental health measures are also plotted in Figures 20 and 21. The dizziness handicap index (DHI) showed a reduction over time for both groups, largely independent of group or playtime (Figure 20B and 21B). The Niigata PPPD Questionnaire (NPQ, figure 20C and 21C) increased slightly for both groups, independent of playtime. Anxiety and depression scores (Hospital Anxiety and Depression Scale, HADS) did not differ between groups in mean scores (Figure 20D, 20E), but did reduce more for higher intervention playtime (Figure 21D, 21E; $r(38) = -0.41$, $p = 0.012$, 95% CI [-0.64,-0.10], $r(38) = -0.49$, $p = 0.02$, 95% CI [-0.70,-0.20], respectively), without correlating with control playtime (see also Appendix 3 supplementary Figure S1 for mean results for participants adhering to recommended playtime).

As part of the time 2 surveys, participants provided qualitative responses to open-ended questions. Only responses from the intervention group (who played Balance-Land in full) are reported here. Several participants thought playing the game had helped (9), e.g. "*My symptoms have improved. Not completely gone, but I really do think the game has helped with the re-hab"*; "*I think I can tolerate more movement, more light, on screen and in life"*; "*I have noticed a significant improvement in my symptoms. I think a combined approach as listed above has definitely helped me'.* Some participants gave examples of improvements to their daily lives: *"Slightly less* *symptoms going through small stores; slightly improved ability to watch traffic at a busy intersection"*; *"Riding in a car has been better, I don't get as sick as I once did";* "*I seem to have a little more tolerance more movement of screens, although there are still some things, like flashing lights that [I] still can't tolerate."* However, many participants (15) reported no major changes: *"I feel just as miserable as always, no changes to symptoms. I felt some minor improvement in the first few weeks of playing"*, or *"Yes after playing the game but overall no"*; *"Most of my symptoms have not changed"*, and others (5) were unsure: *"I generally feel less dizzy, but my dizziness always comes and goes in spells so it's hard to know what it's down to"*; *"Not sure if it's just coincidence but since playing the game I have had far less very bad days in general."* Some participants mentioned anxiety reduction or improved understanding "*I'm less scared of PPPD now";* "*I feel like I'm more aware of what the triggers are from playing the game."*



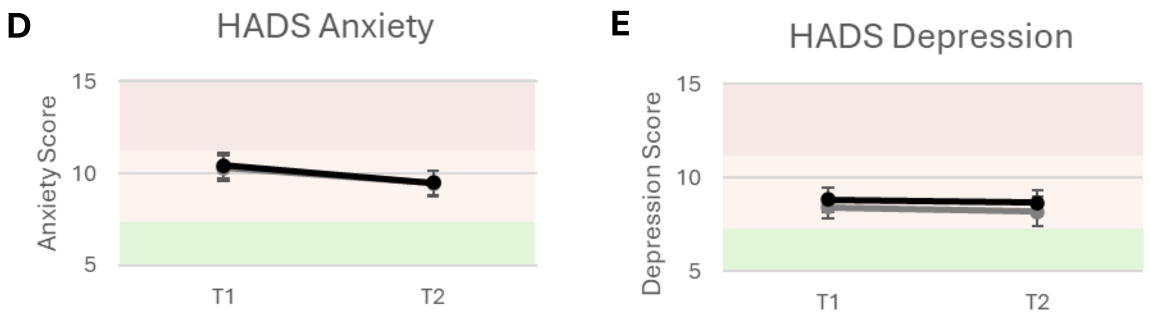
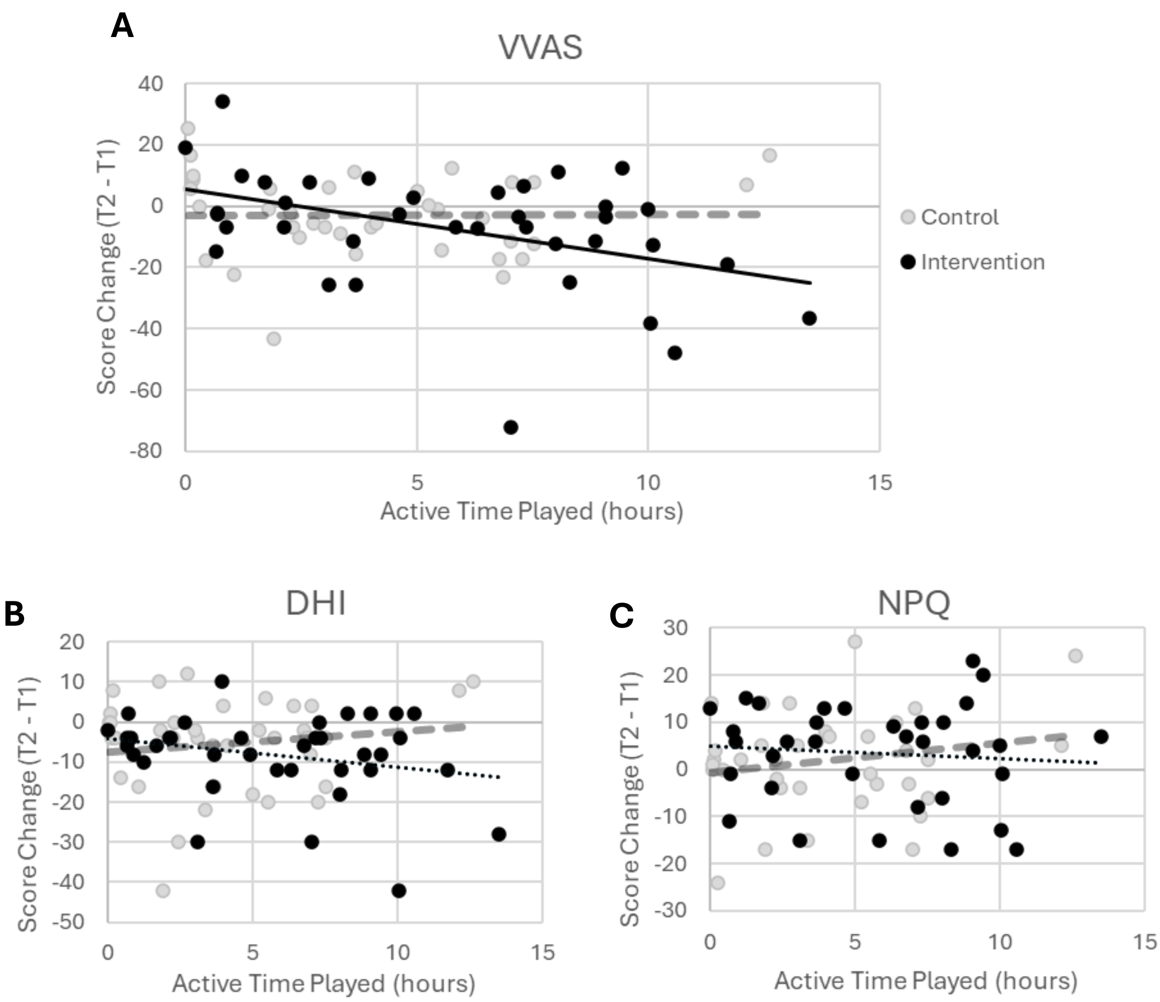


Figure 20, Intention to treat results for rehabilitation effects in primary outcome measure (VVAS, A) and secondary outcome measures: DHI (B), NPQ (C), HADS Anxiety (D), and HADS Depression (E) scores. Shaded areas indicate categories associated with each measure, where available (for VVAS and DHI, pink=severe, orange=moderate; for HADS, pink = clinically diagnosable, orange = borderline, green = normal). Error bars are SEM.



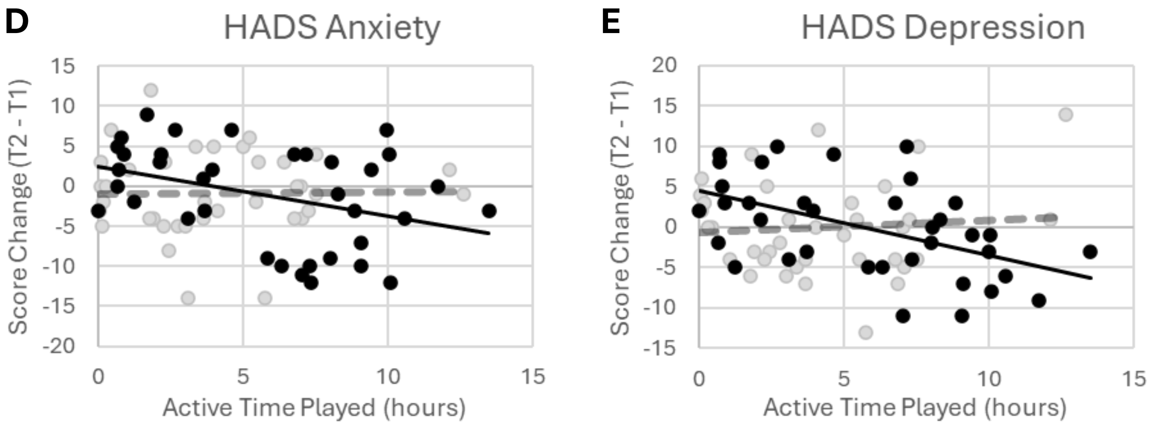


Figure 21, Correlations between active time played (intervention groups only) and changes in VVAS (A), DHI (B), NPQ (C), HADS Anxiety (D), and HADS Depression (E) between Time 1 and Time 2. Solid lines are significant correlations, dashed lines are non-significant. Black lines are intervention correlations and grey are control group correlations.

4.5 System Usability and Enjoyment

We used the System Usability Scale (SUS (Brooke, 1996)) to measure usability. The mean score for the intervention group was 80 (12.8 SD [45, 100]), which is equivalent to the 80^{th} percentile of usability (categorised as ‘highly useable’ (Lewis & Sauro, 2018)). There was no difference between this group and the Control group who only played the word games without having to navigate the virtual zones ($F(2,74) = 0.73$, $p = 0.49$). There were no correlations of SUS with the outcome measures reported above, suggesting that differences in usability do not account for the rehabilitation effects reported. To assess whether all areas of the game were accessible to participants, we compared the locations of player inputs to a map of available locations across the zones (Figure 22). Player inputs were recorded in all usable locations.

A. Desert B. Park C. Supermarket

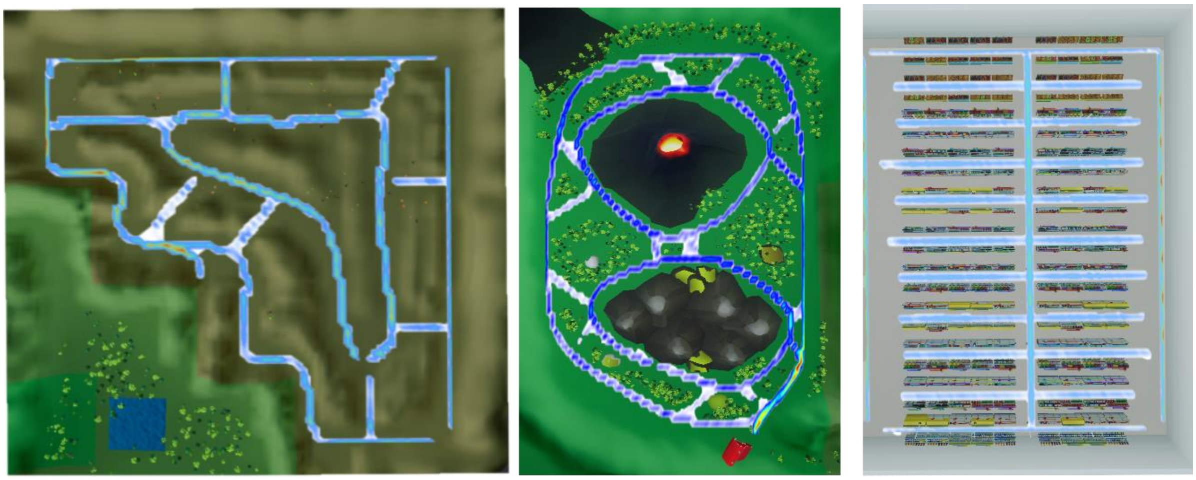


Figure 22, Heatmap of paths taken by participants, overlayed on the three zones of Balance-Land. A darker blue indicates denser inputs, whilst a lighter blue indicates a more even spread of inputs, and white indicates no inputs. Many participants did not input commands whilst transitioning between tracks as letter tiles could not spawn on transition tracks. Participants accessed all areas and used all available pathways. The supermarket had denser inputs due to participants frequently inputting commands to turn down aisles, compared to the looping paths of the other environments. Participants tended not to input commands on longer curved paths.

Participants were asked at time 1 (before accessing Balance-Land) about their digital experience, and of the participants that completed the study, 64 reported using computers nearly every day, while 13 reported using computers about twice a week or less. Only 6 of these infrequent users were in the intervention group and they were as likely to play for the recommended playtime (3) as not (3), indicating no evidence that low digital experience explains low playtime. In exit interview responses, participants reported learning the game as straightforward or easy (15/15), and most (9/15) reported that they had learnt to use the controls within the first session.

Participants were asked to rate their enjoyment from 0 (none) to 10 (high). The mean ratings were 5.9 for control and 7.2 for intervention (7.8 for those playing the recommended time, 6.6 for those with low playtime). There were no significant correlations of enjoyment score with outcome measures for the Intervention Group.

In response to the open-ended questions, some participants (6) spontaneously mentioned finding the game enjoyable: *“The games were great and definitely got easier over time”*. However, some participants expressed frustration (5) with certain aspects of gameplay and many (10) reported difficulty fitting in or sticking to the recommended schedule *“Hard to do as life always interfered!”*. Others reported that they needed reminders *“5-10 minutes was a short amount of time to dedicate out of my day, which made it easy to integrate into my routine. However, it was easy to forget to play the game, especially if my daily routine changed.”*

The participants’ final open-ended question was whether they would play Balance-Land more if there was evidence it reduced symptoms, and how often they would play. Some participants said that the twice-daily playtime we recommended in the trial was enough (12), with reasons relating to daily life *“Absolutely. Twice daily unless unusual circumstances prevent me from doing so”,* and symptom load *“I do not think that I could tolerate playing more than I did and still be able to do other things throughout my day.”* However, the majority (20) responded that they would play more: *“3-4 Times a Day”* and “*yes. I would play at least an hour a day*“, *“Sure, as often as [I] remember to” “Yes I would play 24/7 if I have [to]”* and *“Yes, as often as it took”*. Only 2 participants responded that they would not play the game, and this was because it had not triggered symptoms for them.

4.6 Daily dizziness

To determine whether engagement with the game was associated with symptom severity, initial VVAS score and daily symptom ratings were correlated with active playtime for the intervention group. There was no correlation of playtime with Time 1 VVAS symptoms ($r(37)=0.26$ $p = 0.12$), but there was a correlation with the daily diary symptom ratings (Figure 23, $r(36)=-0.41$, $p = 0.013$), such that people with a lower daily symptom rating before playing Balance-Land tended to play for longer or more often. There was no correlation between playtime and daily post-play symptom rating ($r(35)=-0.24$, $p = 0.17$). In the daily diaries we also asked if participants had done other vestibular rehabilitation; however, this data predicted neither game playtime nor evoked symptoms.

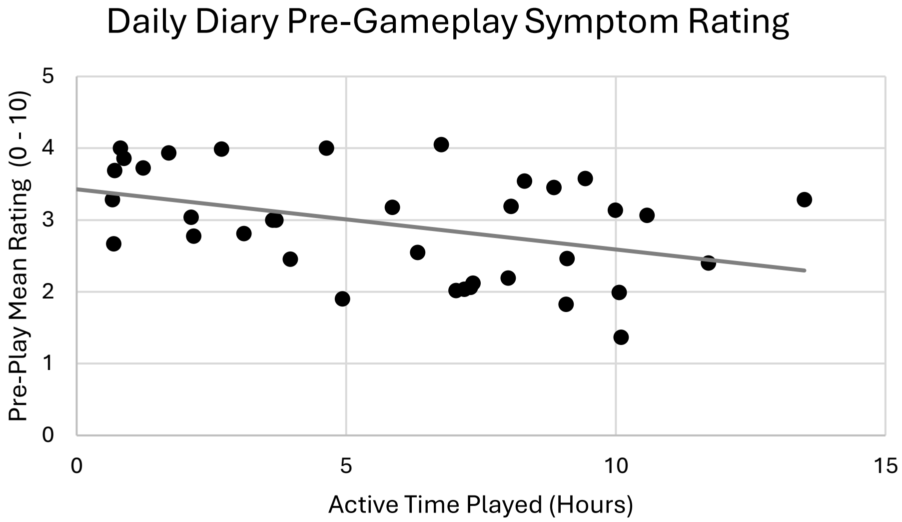


Figure 23, The mean of participants' daily symptom rating before-gameplay (how severe symptoms were before playing) correlated with their active time played in hours (plotted for intervention groups).

4.7 Discussion

Debilitating visually-induced dizziness, such as occurs in PPPD and other conditions, is very difficult to treat. In this online feasibility study we aimed to assess the potential usefulness of embedding visual desensitisation within a game context to allow graded exposure to visual motion in virtual environments and allow everyday usage at home. If useful, this approach could become a rehabilitation option as part of a wider treatment package.

4.7.1 Rehabilitation Effectiveness

The reduction in visual vertigo symptoms (VVAS) in participants who chose to play Balance-Land for the recommended time converge with prior findings (Pavlou et al., 2013) that viewing visual flow patterns reduced symptoms of visually-induced dizziness. Interestingly, daily diary symptom levels before and after gameplay were not significantly different between the intervention (visual flow) and control (no visual flow), meaning that although control condition puzzle games triggered some symptoms, merely triggering symptoms with non-motion stimuli may not be sufficient for rehabilitation (Popkirov, Stone, et al., 2018).

We also found that anxiety decreases correlated with playtime for the intervention group, but not the control. This reduction in anxiety scores was at a clinically meaningful level for many participants engaging with the game recommendations. Anxiety is known to be a strong precipitating and maintaining factor in PPPD (Popkirov, Stone, et al., 2018; Staab et al., 2017; Staab et al., 2014) and a correlate of visually-induced dizziness and sensitivity to visual stimuli across all conditions where it arises, as well as in the general population (Powell, Derry-Sumner, Shelton, et al., 2020). Therefore, supporting improvements in anxiety may be as important for rehabilitation and quality of life as targeting dizziness itself. Recently, other research has highlighted the beneficial effect targeting anxiety can have for PPPD recovery (Herdman et al., 2022), and many clinicians who provided feedback on game development reported prioritising anxiety treatment ahead of vestibular exercises for dizzy patients. The qualitative data indicate that anxiety reduction may be a consequence both of becoming more self-aware of triggers, and of being exposed to triggering environments in a safe and controlled manner (with easy escape).

We also found some differential reduction in depression scores, which is often correlated with anxiety. We did not find differential rehabilitation effects in the DHI or NPQ scores. The reasons for this remain unclear and could not be explained by separating the NPQ into subscales (visual vs postural (Yagi et al., 2021)) or incomplete answers for our diverse participant group (Castillejos-Carrasco-Muñoz et al., 2023). Of note, the VVAS score change correlated with the DHI score change ($r(37) = 0.55$, 95% CI [0.27,0.74]) and the NPQ score change ($r(34) = 0.60$, 95% CI [0.31,0.77]), as they would broadly be expected to, providing no evidence that one or more questionnaires were being filled out incorrectly.

Taken together, we have preliminary evidence, albeit with a small sample size and only in people self-selected for playtime, that visual desensitisation within a game environment may be effective in lowering visually-induced dizziness and anxiety. The mechanism is most likely to be the same as the visual optokinetic paradigms that inspired the creation of Balance-Land (Mandour et al., 2021; Nada et al., 2019; Pavlou et al., 2013; Popkirov, Stone, et al., 2018; Teh et al., 2023). Future research is needed to confirm these effects in a larger population and to see if they are maintained over a longer time frame.

4.7.2 Attrition, adherence, and self-selection

Attrition and adherence to recommended playtime were clear challenges in the feasibility study and need to be further addressed to enable future research or clinical use of Balance-land. Overall, 45% of participants who completed Time 1 assessments withdrew before completing Time 2. This is not unusual for unsupervised rehabilitation (e.g. Pavlou et al (Pavlou et al., 2013) report 55% dropout in their unsupervised group). For those who did complete Time 2, ten participants mentioned difficulties fitting the sessions into their daily schedules and less than half of participants played the recommended amount (at least 10 minutes a day on average). It is worth noting that vestibular rehabilitation is normally recommended for 10 minutes a day as a minimum (unless severe acute symptoms prevent this), and without such time commitment rehabilitation progress would not be expected.

Importantly, we warned participants at the beginning of the study that there was currently no evidence that Balance-Land could improve symptoms, and this is a key factor that likely affected motivation. Of the intervention participants responding to the exit survey, 34 said they would be happy to play Balance-Land at the recommended dosage if evidence suggested it could improve symptoms, and 22 of these said they would play for longer than the 5-10 minutes twice daily we recommended in the study. Therefore, it appears that a key '*chicken and egg*' difficulty for research engagement is the lack of such evidence beforehand.

For participants who withdrew, the reason for withdrawal was not known in many cases and could have created bias. Of the reasons reported, common reasons were co-occurring health issues (6), technical difficulties (3), and time commitment (2). Two participants withdrew because they attempted to play levels within the game that were too intense and triggered too many symptoms. However, overall withdrawal was not related to VVAS severity at Time 1 or digital experience. Of the unknown reasons, it is possible that participants who did not think that Balance-Land was reducing their symptoms were more likely to withdraw, potentially creating a self-selection bias in the findings. This kind of attrition is common in both home settings and hospital-based rehabilitation therapies (Teh et al., 2023). One advantage here was that many participants reported not knowing which group they were in (they did not unblind themselves based on what kinds of gameplay they saw), making it less likely that unknown attrition reasons were markedly different across groups.

However, a second kind of self-selection was introduced by whether participants played for the recommended time or not. To meaningfully assess rehabilitation promise, we assessed correlations with playtime (and in Appendix 3, we plot results for adhering participants only, breaking the randomisation of participants). Fortunately, those who played or did not play for the recommended time did not show major differences in VVAS severity, duration of symptoms, or age, in any direction likely to account for the group differences we found (Table 1). However, there may be other differences between participants that influenced, or correlated with, their chosen playtime. For example, perceiving that their dizziness was improving may have been a motivation to keep playing, rather than (or as well as) a consequence of playing. Another difference is in the proportions of reported diagnoses (see Appendix 3, albeit with the caveat that diagnoses are not always correct, as discussed above). Numerically more participants with low playtime reported a PPPD diagnosis, which is known to be difficult to rehabilitate. Although PPPD is one of the key conditions targeted by the game, the complexities of PPPD and other comorbid conditions will impact rehabilitation success and / or may make engaging with the game more difficult.

The daily dizziness ratings may partially explain differences in adherence, where lower pre-play symptoms correlated with higher playtime. This may be interpreted as indicating that higher daily symptoms are a barrier to engaging with symptom-provoking rehabilitation (though note that daily symptom ratings may also partly reflect the improvements over time for those playing the game more). One of the key aims of Balance-land was graded stimulation to allow an entry point to rehabilitation even for those with severe symptoms. A graded and slow build-up may need to be better explained and planned for participants in future. We did not block participants from quickly engaging in the more complex zones or using faster speeds and some participants chose levels that they could not tolerate in the very first play sessions (despite advice not to).

4.7.3 Digital Accessibility and enjoyment

The System Usability Scale (SUS) scores and the exit interviews indicated Balance-Land was accessible to a range of users, across a range of ages and digital experience. We identified no barrier for those with lower digital experience. However, participants who struggled with accessibility may have withdrawn from the study, although only one person gave this as a reason for their withdrawal. Participants were recruited online and thus self-selected for some degree of computer use. Interestingly, participants who found Balance-Land more useable also reported experiencing more symptoms after playing it. One explanation for this might be that better understanding of how to play the game helped people to more effectively expose themselves to visual flow and trigger symptoms. Reassuringly, enjoyment was rated moderately highly, although a game aimed primarily at rehabilitation is not ever likely to be as enjoyable as commercial games aimed primarily at enjoyment. The puzzle game play was chosen to engage older demographics (Chesham et al., 2017; Salmon et al., 2017) and we interviewed participants directly during development(Goodwin et al., 2023). We also know that immersion aids enjoyment and motivation (Weibel & Wissmath, 2011), which was one of the reasons for aiming to mimic real-life environments.

4.7.4 Balance-land in practice

The aim of Balance-Land is not to replace other kinds of rehabilitation therapy. We hope that Balance-land can become part of a multi-faceted treatment approach for patients experiencing visually-induced dizziness. It utilises already-evidenced principles of optic flow desensitisation and we have found no indication of detrimental effects, other than the symptoms expected to be evoked by rehabilitation.

A key advantage of Balance-Land is that rehabilitation intensity can be increased gradually. Recommended playtime and intensity of visual exposure will need to be calibrated for different patients and potentially built up in a rehabilitation schedule over several weeks, exactly as current visual desensitisation therapy is scheduled. We will therefore put tighter controls in place to limit access to the higher levels of intensity until players have built up experience in the game. We recommended playtime of 5-10 minutes twice a day in the trial based on discussions with clinicians and our patient advisory group about likely feasibility and symptom evocation, but it is likely that higher dosage would be desirable if tolerated. For example, Pavlou et al. (Pavlou et al., 2013) used up to 45 minutes a day for optokinetic desensitisation.

Importantly, Balance-Land is a web-based application requiring no specialist equipment. Ideally, Balance-land should be played on the largest screen available to patients to maximise visual field, but some participants in our study used tablets (presumably with shorter viewing distance, but this was not measured). Balance-Land can be adapted to work on phones, however the necessary field of view for visual desensitisation is not known.

4.8 Conclusion

The goals of this feasibility trial were to assess Balance-Land's: usage in a varied cohort with visually-induced dizziness; rehabilitation potential; system usability and enjoyment; relationship with daily symptoms. Around half of participants completed six weeks of playing Balance-Land, and about half of those played for at least an average of 10 minutes a day. For the latter group, there appeared to be rehabilitation effects in reduced visually-induced dizziness, anxiety and depression, though other explanations are possible given they self-selected for gameplay time. System usability was high and some participants with relatively low digital experience engaged successfully with the game. Moderate enjoyability was reported, but like all vestibular rehabilitation, Balance-Land evokes symptoms and those with higher daily symptoms tended to play less, suggesting that managing symptom load through even more graded exposure is critical for engagement. Further research is required in a clinical setting.

5 Chapter 5: Investigating factors affecting participants of Balance-Land

5.1 Introduction

The previous chapter provided evidence there was a positive correlation between the active time a participant played and their VVAS (Bronstein, 1995) score change between Time 1 and Time 2, for the intervention group. This means the more the participant played, the lower their VVAS score was expected to be, with a lower VVAS score being indicative of the participant experiencing fewer visually induced dizziness symptoms. There was also a correlation between how long a participant played overall and the average daily symptom ratings before they played.

However, Chapter 4 did not analyse what factors affected participant's daily symptom severity, nor what factors affected how long participants played for in an individual day or session. Both questions are important, with participants giving severe symptoms as a reason to not play more and with the latter question directly implicated in the playtime correlations from Chapter 4. Using the data gathered from participant gameplay and the daily diary participants filled out, we can address these questions.

Visual flow stimuli have been shown in the past to evoke participant's symptoms (Law et al., 2024; Mandour et al., 2021; Pavlou et al., 2013), which was the primary reason the environments were designed in such a manner. If this were successful in Balance-Land, we would expect to see the participant's diary symptoms increasing by a larger margin after playing Supermarket than Desert or Park, due to Supermarket being designed to have more intense visual flow stimuli. However, this ignores the rate of visual flow. A participant playing on the maximum speed for 5 minutes would experience more visual flow than a participant that utilised half speed for 5 minutes (Beauchemin & Barron, 1995). As such, any investigation into the different environments must include participant speed in some fashion.

A different explanation that can explain daily symptom severity and playtime could be that of frequency or periodicity, rather than the complex environments. Whilst a participant with a higher active play time played for longer, it is unclear whether there was any effect of when the participant played. For example, playing Balance-Land for 10 hours may have a similar effect to playing 5 minutes twice daily for 60 days. Traditional vestibular rehabilitation courses recommend spacing out the rehabilitation (Alrwaily & Whitney, 2011; Han & Han, 2021; Whitney & Sparto, 2011; Whitney et al., 2020), which mirrors the recommendations given to participants in Chapter 4. By looking at the total duration of a play session, the play time in each environment for the session, and when during the feasibility study the data came from, we can determine whether a participant should focus on one environment, a mixture of environments, longer play sessions, or consistency of play.

Balance-Land was envisioned as a tool that clinicians can utilise as part of their kit to treat visually induced dizziness. As such, the feasibility trial did not ask participants to stop other forms of vestibular rehabilitation and encouraged participants to keep acting as they normally would. Prior research has given evidence that a combination of rehabilitation types is the current best-practice recommendation for vestibular rehabilitation (Popkirov, Stone, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023) and as such we may expect an effect on those participants that did concurrent vestibular rehabilitation.

The actions of participants whilst playing were recorded, and participants filled out a diary when they played Balance-Land. This allowed data from the diary, such as before and after play symptom scores, duration of symptoms, and concurrent vestibular rehabilitation, to be combined with gameplay data, such as length of play in each environment, speed utilised, and the date the game was played. To account for differing baseline symptoms and since participants rated their symptoms before play and after play on the same scale, a relative difference score can be created by subtracting the before score from the after score, ideally isolating the effect of playing Balance-Land. Utilising data from the feasibility study (Chapter 4), we can further investigate factors that affect rehabilitative promise and engagement, respectively:

1) What factors affect the increase in symptom severity during a Balance-Land session?
2) Is there evidence that daily symptoms or other measured factors affect the duration of a Balance-Land session?

The two questions can be investigated with two linear mixed models, with symptom severity change and mean session duration as dependent variables, respectively.

5.2 Methods

5.2.1 Participants

For this analysis, we were concerned with how different factors affected participant interaction with Balance-Land. As such, the control group were excluded from the analysis as they did not interact with Balance-Land. A game session is when a participant logs into the game to play and may involve the participant playing multiple environments. All game data from participants in the intervention condition were used, which meant 1181 possible game sessions could be linked to diary entries from 37 participants.

5.2.2 Diary Data

Whilst participating in the feasibility study in Chapter 4, participants were asked to fill out a diary each time they played, answering two questions before they played, and two questions after they played:

(Before): When you last played the game, how long did your symptoms persist afterwards?

This had six responses: I did not experience symptoms; Less than 5 minutes; Around 15 minutes; Around 30 minutes; Around 1 hour; 2 hours or more.

(Before): Before playing Balance-Land today, how severe are/were your symptoms?

(After): After playing Balance-Land today, how severe are/were your symptoms?

Participants responded with a 0, 2, 4, 6, 8, or 10, with a smiling face at 10 morphing into a sad crying face at 10.

(After): Have you done any vestibular rehabilitation, apart from the game, since you last answered the diary?

Participants responded yes or no to this question.

Participants were asked to fill out their Diary each time they played Balance-Land. Whenever a participant logged into Balance-Land to play, the Diary questions would open in a separate tab for them to answer with their login ID (player ID) as a reference link, ensuring all Diary entries could be attached correctly to their participant. Some participants filled out and submitted the two “before” questions, played Balance-Land, then submitted the two “after” questions, rather than using one Diary entry to answer all four questions. Diary entries that were made within an hour of each other and following this pattern (“before” filled out with no “after”, and “after” filled out with no “before”) were combined into a single entry. Each diary entry was then assigned a diary identification (diary ID) number.

A symptom difference score was calculated by removing the before-play symptom score from the after-play symptom score (after – before). This means a positive score is a relative increase in symptoms and a negative score is a relative decrease in symptoms. If a diary entry was missing either of the scores, no difference score was calculated.

5.2.3 Game Data

Whenever a participant logged into Balance-Land they were assigned a unique game identification (game ID) number. Whenever a participant did something in-game (e.g. click a button, pick up a tile), the location, time input occurred, game ID number, participant identification (participant ID) number, and type of action were recorded, along with a unique in-game session identification (in-game session ID) number. Using the location data, each in-game session ID was then allocated a location that it occurred in (Spawn, Desert, Park, or Supermarket) and the time data allowed the calculation of the duration of the game ID and time between consecutive in-game session ID data. Only data from the intervention group was utilised.

5.2.4 Linking Diary and Game Data

The game ID was tied to a diary ID if the diary entry occurred 3 hours either side of the game ID. This was done to allow time for participants to fill out the diary if they forgot, or the diary got combined into the before play diary entry in the event of a combined diary entry (see section 5.2.2). This resulted in 931 of the diary entries being linked to a possible 1181 game IDs of intervention participants. Game IDs with no diary data were not used in the analysis.

5.2.5 Data analysis

To determine which, if any, factors affected participant symptom increase, a linear mixed model was conducted with the symptom score difference (after – before) as the dependent variable, giving a range of -5 to 5 (1 – 6 to 6 – 1). This was chosen rather than the after score alone to account for baseline variance between participants. The participant ID was entered as a cluster variable, whether they did vestibular rehabilitation before playing the game mode (1 for yes, 2 for no) was entered as a factor. The following were entered as covariates: the playtime in each environment (time over 30 minutes in an environment was discarded as the participant being absent from their computer, and playtimes were expressed as a percentage of 24 hours, resulting in 0.00694 being 10 minutes, the week the game took place in relative to their start time (0 to 6; 0.5 would be 3.5 days into the study, 2 would be 14 days into the study, et cetera), the prior symptom duration from last time participants played Balance-Land in the diary (1 to 6), and the mean speed percentage (from 0 to 1). The intercept, along with all covariates and factors, were entered as random effects assumed to randomly vary across participants.

The mean speed percentage was calculated via multiplying the time spent at a speed by the speed, divided by the total duration of the game session. This results in a possible speed of 0 for no movement and 1 for a participant only ever using the maximum speed. Clicking the centre arrow at the start of play set the movement speed to 0.3, with 25 game IDs occurring with participants clicking the arrow and never touching the movement speed slider. These had their mean speed percentage set to 0.3.

To investigate what affected how long a participant played for, a linear mixed model was conducted with the total playtime of a game session as the dependent variable. If the participant was missing any of their individual environment playtimes due to outlier removal, their total playtime of a game session was not calculated. This value was then converted into a percentage of an hour instead of percentage of a day, for easier visibility. The participant ID was entered as a cluster variable, with vestibular rehabilitation as a factor. The following were entered as covariates: the before-play symptom rating (from 1 to 6), the after-play symptom rating (from 1 to 6), the mean speed percentage (from 0 to 1), prior symptom duration (from 1 to 6), and week entered (0 to 6, as above). The intercept, along with all factors and covariates entered as random effects assumed to randomly vary across participants.

Data were excluded if they contained any missing information, except duration of location play, which required a minimum of one location played in (Desert, Park, or Supermarket). With all exclusions in place, there were 841 game IDs linked with diary entries with data across 35 participant IDs for the symptom difference linear mixed model, which decreased to 824 entries across 35 PIDS for the duration of play linear mixed model, from a possible 931 linked diary and game IDs.

Putting in all factor combinations for analysis would result in 127 and 63 comparisons, respectively. Not all of these combinations would be of theoretical interest and multiple comparisons correction would make the p-values extremely low. As a result, only the main effects were analysed, which resulted in 7 and 6 comparisons for each linear mixed model instead, respectively.

5.3 Results

To gain evidence on what may have affected the participants' symptom severity increase, a linear mixed model was conducted with the symptom difference (after play symptom rating – before play symptom difference) as the dependent variable. See the data analysis section for specifics.
For the linear mixed model, $R_c^2 = 0.34$. Out of the 7 analysed factors, 1 was significant:

Table 2, Linear mixed model estimates for the symptom difference and the 7 factors of interest. Significant factors are in bold.

Parameter	Beta Coefficient	95% CI	Standard Error	t (degrees freedom)	p-value
Week	**-0.10**	**-0.16, -0.05**	**0.03**	**-3.64 (13.54)**	**0.003**
Prior Symptom Duration	-0.02	-0.05, 0.02	0.02	-0.87 (67.39)	0.390
Vestibular Rehabilitation	0.07	-0.05, 0.19	0.06	1.15 (49.25)	0.255

Mean Speed Percent	-0.03	-0.29, 0.24	0.14	-0.19 (6.55)	0.856
Mean Desert Playtime	8.54	-5.83, 22.91	7.33	1.16 (232.69)	0.245
Mean Park Playtime	10.25	-4.43, 24.93	7.49	1.37 (356.55)	0.172
Mean Supermarket Playtime	9.81	-4.63, 24.25	7.37	1.33 (406.37)	0.184

The negative beta coefficient for week implies the symptom difference decreased as week increased, as shown in Table 2. Week cannot be bi-directional as it is a time-based variable, this indicates week negatively affected the increase in symptom severity during a Balance-Land session: as participants took part in the feasibility trial, their symptoms did not increase as much as at the start of the feasibility trial.

To gain evidence on what may have affected the duration of a Balance-Land session, a linear mixed model was conducted with the mean total duration of the game session as the dependent variable. See the data analysis section for specifics. For the linear mixed model, $R_c^2 = 0.09$. Out of the 6 analysed factors, 1 was significant:

Table 3, Linear mixed model estimates for the mean session duration and the 6 factors of interest. Significant factors are in bold.

Parameter	Beta Coefficient	95% CI	Standard Error	t (degrees freedom)	p-value
Week	0.001	-0.003, 0.007	0.003	0.64 (20.0)	0.532
Prior Symptom Duration	**0.006**	**-4.24×10^{-4}, 0.01**	**0.003**	**2.12 (31.6)**	**0.042**
Vestibular Rehabilitation	-6.24×10^{-4}	-0.02, 0.02	0.01	-0.06 (12.5)	0.954
Mean Speed Percent	-0.015	-0.05, 0.02	0.02	-0.90 (22.1)	0.380

Before session rating	-0.009	-0.02, 0.002	0.01	-1.53 (30.8)	0.137
After session rating	0.010	-0.01, 0.02	0.01	1.54 (26.9)	0.134

Similar to the first linear mixed model, prior symptom duration is a time-based variable and cannot be reverse influenced from current play (see Table 3). This indicates the longer participants reported symptoms lasting the prior time they played Balance-Land, the longer they would be likely to play. Whilst this initially seemed counterintuitive, there are possible explanations: participants that noticed longer symptoms could be more likely to recognise Balance-Land as having an effect, and therefore were more likely to play for longer; alternatively, participants have a habit and did not want to alter their play patterns. There could potentially be a stimulation effect too: participants played slower or took more breaks not looking at the visual stimuli (compensation or not moving) and thus this resulted in longer play times. It is worth being cognizant the $R_c^2 = 0.09$, which is small, and the estimate = 0.01 was similarly small.

5.4 Discussion

The linear mixed models have answered the two questions: symptom difference ($R_c^2 = 0.34$) was affected by the week the participant played the game session in ($\beta = -0.10$); mean playtime of a game session ($R_c^2 = 0.09$) was affected by the prior duration of symptoms ($\beta = 0.01$). The first linear mixed model showed playing Balance-Land towards the end of the feasibility study (a higher week count) has a smaller effect on evoking daily diary symptoms than at the start of the feasibility study. The second linear mixed model showed participants that reported longer lasting symptoms the last time they played tended to play for longer the next time.

Delving into the first linear mixed model, the best explanation is that of visual desensitisation. Participants that played Balance-Land became desensitised to the complex visuals the more they played, resulting in less of a daily symptom increase. This is a possible explanation and, if true, would provide support for Balance-Land as a visual desensitisation rehabilitation tool. This could then explain the observed VVAS decrease in Chapter 4, if the lowered triggering of symptoms by the game translates to generally lowered symptom evocation in everyday life (Moaty et al., 2017; Pavlou, 2010).

The second linear mixed model findings could be plausibly explained by the use of coping strategies, which is a response to an aversive situation, typically aiming at reducing levels of distress (Carver et al., 1989; Wechsler, 1995). A participant with longer-lasting symptoms the last time they played may find those feelings unpleasant and wish to change this. As a result, the next time they play, they employ coping strategies to reduce the visual stimulation. For example, if the participant closed their eyes or looked away as a coping strategy, such as reported in Chapter 3, the participant would be doing nothing meaningful whilst not looking at the screen or with closed eyes. This would be reflected in the data as no progression towards gaining points or completing a level, which was observed.

The use of coping strategies could also explain why there was no significant effect of environments. The visual flow was adjustable primarily through participant speed, which was included in both linear mixed models and was non-significant, but participants in Chapters 3 and 4 both reported utilising coping strategies to lower visual stimulation, which was not included in the model. Rather than using the speed to moderate the visual flow, the participants used an easier alternative: looking away from the screen or closing their eyes. Participants were instructed to do this if stimulation was too intense, but it was meant to be the step after reducing the speed. Why a coping strategy would be utilised instead of the available tools to reduce visual stimulation would be because it is easier, faster, and had immediate effect. This can be solved in the future by making visual flow control easier to implement than the coping strategies, although it is unclear what change would accomplish this. Unfortunately, lacking eye-tracking data, we were unable to account for the use of coping strategies. Webcams are now usable as eye trackers (Wisiecka et al., 2022; Yang & Krajbich, 2021), meaning future experiments could account for this.

This is not the only explanation for the second linear mixed model. An equally viable explanation is that participants formed habits around how they played and were resistant to change. What is meant by this, is that participants formed a routine, such as waking up, getting dressed, then playing Balance-Land before work, and were unwilling to alter their routine despite negative outcomes. This would be in-line with theories on how visually induced dizziness can develop, with maladaptive coping strategies being employed (Staab et al., 2017). However, it is unclear whether this is an issue: the participants that engaged with Balance-Land managed their symptoms effectively, as demonstrated by the data in Chapter 4, meaning encouraging changing a habit would not be necessary. Regardless of which explanation was correct, it must be re-iterated that the second linear mixed model $R_c^2 = 0.09$, which is small, and the estimate = 0.01 was similarly small, which makes it more likely that the actual mechanism was not measured.

One important aspect that did not appear to have an effect in either model was that of concurrent vestibular rehabilitation. There was no evidence Balance-Land with concurrent vestibular rehabilitation affected the provoked symptoms or altered gameplay behaviour, but this was partially expected. The measure of vestibular rehabilitation was a binary "Yes/No" and did not allow for the form of rehabilitation. Prior research indicates a multi-pronged approach to rehabilitation being the most effective (Popkirov, Stone, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023). Not all forms of vestibular rehabilitation work in the same manner and can take different forms, such as cognitive behavioural therapy (Herdman et al., 2022), visual desensitisation (Pavlou et al., 2013), pharmacological intervention (Horii et al., 2016), or other non-pharmacological interventions (Webster et al., 2023).

Exploring the relationship between Balance-Land and different types of vestibular rehabilitation is important, as it directly effects the best practice treatment for any patient utilising Balance-Land. We might expect rehabilitation that focuses on cognitive behavioural therapy (Herdman et al., 2022) to have a larger effect on how participants approach Balance-Land, such as trying more challenging environments (higher play time), compared to visual desensitisation (Pavlou et al., 2013) having larger overlap with what Balance-Land is aiming to accomplish. Not only that, but as currently measured, we might expect concurrent vestibular rehabilitation to affect participant behaviour on other symptom-related measures, showing as an interaction effect rather than showing up as a main effect itself, as it would make participants more aware of their triggers, their symptoms, and how best to manage them, as shown in participant comments in prior chapters. The best way to explore this, and many other questions raised from these results, such as the utilisation of coping strategies, would be via a randomised control trial (Krauss, 2018).

The implications of what was not found in the two linear mixed models provide more context to data in Chapter 4: namely diary before-play ratings correlated with active play time, which then would be expected to show up in the second linear mixed model of the mean Balance-Land session play time. The most likely explanation for not finding significant factors is that the two datasets used were slightly different. The linear mixed models only included diary data that could be assigned to a game session, whereas the Chapter 4 finding utilised all diary data that was complete. This translates into the Chapter 4 correlation having more diary entries in the analysis and thus more power. We do not suspect that diary entries without corresponding game session data to be invalid, because this can be explained by participants having internet connection issues after starting to play, which would disrupt data communication. It seems unlikely that a participant would choose to fill out a diary entry, which opens when they log-in to Balance-Land, but then not initiate a game session, especially when in the majority of instances this was not the case.

5.5 Conclusion

There is evidence that a participant's relative symptom increase from playing Balance-Land decreases over time, a sign of desensitisation to the stimuli used. Taken with the active playtime and VVAS correlation from Chapter 4, which indicates that consistently playing Balance-Land results in a larger decrease in VVAS score, Balance-Land appears to work as a form of visual desensitisation rehabilitation. Participant prior symptom duration was the only factor to affect playtime, which was surprising. This is likely due to either coping strategies or habit formation, which can be tested via webcam-based eye-tracking. There was still a large self-selection bias in the data, meaning the participants that dropped out of the study may have differing factors affecting them. However, Balance-Land as currently implemented, has stronger evidence for use as a rehabilitation tool.

6 Chapter 6: Final changes to Balance-Land

6.1 Introduction

Results from Chapter 4 and Chapter 5 provide evidence of Balance-Land being able to work as a rehabilitative tool. Chapter 4 showed participants rated Balance-Land in the 80th percentile for usability (Lewis & Sauro, 2018), with mixed evidence for the research goal of engagement. Additionally, one of the issues noted in Chapter 4 was the self-selection bias that was introduced when participants voluntarily dropped out of the study, with 45% of participants dropping out. Other research has found large numbers of participants will drop out, for example 55% of participants dropped out in the unsupervised condition of Pavlou et al. (2013). However, the supervised groups in Pavlou et al. (2013) only reported a 10% dropout rate, far lower than the feasibility study in Chapter 4. As such, there must be changes made to Balance-Land to reduce the dropout rate and encourage participants play for the recommend rehabilitation duration. Gamification is a tool well suited to achieve this (Sardi et al., 2017), but there are many possible ways to enhance the game features in Balance-Land.

The first step was to identify why participants dropped out. Most participants did not give a reason for dropping out, with the highest number (6) citing other health issues as the primary cause. The implication from their withdrawal reasoning being the added strain of playing Balance-Land would be too much for the participants to cope with in daily life. There are two ways this can be alleviated: better onboarding to Balance-Land with clearer warnings; and easier to access controls to alter the visual stimulation whilst playing Balance-Land. More information allows participants to know their symptoms would not increase by much as a result of playing, and more control over stimulation allows participants to stop symptoms if they start being triggered excessively.

The other reasons given for dropping out had (2) participants explicitly report evoked symptoms as too severe, and another (1) participant reported no noticed effect as a reason. For the participants that found Balance-Land too stimulating, limiting the environments they can initially explore until they understand how many symptoms Balance-Land triggers would be a simple and effective solution, but would reduce autonomy which could lead to less internalised motivation (Gagné & Deci, 2005). For those that found Balance-Land not stimulating enough, there already exist other avenues available to them for rehabilitation. Regardless, the solutions to reasons given by participants that dropped out of the feasibility study cannot be fixed via gamification or motivational rewards, as the reasons are not about motivation. However, it is likely some participants did drop out from a lack of motivation, as only 16 of the 62 participants provided a reason in the feasibility study, and these could be solved via gamification. However, this presents two initial issues: identifying the problem these participants had with the currently implemented forms of gamification; and finding a new form of gamification that aligns with the participant.

The gamification implemented in the Chapter 4 feasibility study were forms of external motivation (Gagné & Deci, 2005): points, levels, financial reward for study participation, e-mail reminders, and number of different words found. From participant feedback in the feasibility study, we also know some participants chose whether or not play Balance-Land based on their current symptom level, or whether they felt Balance-Land was having an effect, but this was not a large enough population of participants to be revealed in the data. Taken together, it appears the initial forms of external motivation were effective: all participants did start playing Balance-Land.

Unfortunately, the external motivators were not sufficient to create a more internal shift in motivation, likely a result of lacking two of: autonomy, competence, and relatedness (Deci et al., 1994). It is likely that autonomy and relatedness are the missing pillars for the internal motivation shift: there were no relatedness features implemented in the feasibility study (a lack of relatedness); participant comments revealed the participant felt they could not sufficiently control the stimulation in Balance-Land to a comfortable level (a lack of autonomy); and participants did not play if they did not feel like Balance-Land had an effect, or had a negative effect, essentially meaning that the participant felt their actions did not have consequences (a lack of autonomy). As such, any new form of gamification must target increasing participant autonomy or relatedness.

One of the issues with implementing new forms of gamification is that this adds additional complexity to Balance-Land. Balance-Land has intentionally been kept as simple and as easy to play as possible so it is accessible to the wide demographic of patients with visually induced dizziness (Dieterich et al., 2016; Neuhauser, 2016; Strupp, 2003) and technological ability, as evidenced by participant computer-use responses in Chapters 2 & 4, of the intended users of Balance-Land. Data gathered from Chapter 2, where no participants played the tutorial as it was optional, and Chapter 4, where some participants ignored written and in-game instructions on how to start playing and how to adjust intensity to not overstimulate, echo the findings of Beltran et al. (2012): participants ignored many instructions and acted as they saw fit. This means the first and most important concern for any new forms of gamification to improve the dropout rate must require as minimal input from participants as possible, or be so intuitive and easy-to-use to require no, or minimal, training to utilise.

A form of gamification that requires minimal participant input is something that rewards the participant for doing something they already do. As an example, points are awarded to participants for playing Balance-Land in the intended manner, that is collecting letters or items, reinforcing the correct behaviour to better facilitate rehabilitation. Feedback from Chapter 3 indicated participants would be interested in their high-scores for environments, with this potentially being able to be extended into a community-based gamification effort, such as a leaderboard, which would increase relatedness. One other method of gamification is that of unlocking progression. This has become ubiquitous in gaming, with new games and old (e.g. (Bardzell et al., 2012; Entertainment, 2004; Kelly, 2013) drip-feeding content to participants to extend engagement.

Investigating a broader spectrum of gamification options, Stinson et al. (2013) implemented: badges, which were awarded upon completion of certain activities, such as achieving a threshold of experience points or completing a task; and video affirmation, providing participants with positive reinforcement. This positive reinforcement would likely increase feelings of competence in participants, but participant comments indicates autonomy and relatedness should be targeted to better internalise motivation (Deci et al., 1994). Badges are not inherently problematic, but they could become so if participants are primarily motivated to earn them rather than engaging in the intended activity for its inherent benefits (Stinson et al., 2013), which would turn participant focus away from rehabilitation. Likewise, video affirmation most likely would increase motivation in the short-term but run the risk of being generic or insincere and the feasibility study did not find issues with feelings of player competence.

Cafazzo et al. (2012) utilised external rewards, in their case iTunes, for their participants and this proved effective, as this essentially cash rewards participants for their behaviour. There is some doubt that this would work as a motivator, as participants in Chapter 4 were offered monetary compensation and still achieved a 45% dropout rate. Due to ethical concerns, participants were paid regardless of whether they completed the feasibility study. Additionally, this goes against the design principles of Balance-Land, which was to be low-cost and widely accessible form of vestibular rehabilitation. This form of gamification would add to the long-term cost of keeping Balance-Land viable as a form of rehabilitation, which competes with the cost of development of new features.

Healthcare gamification has predominantly focused on motivational rewards such as experience points, badges, or external rewards (Cafazzo et al., 2012; Sardi et al., 2017; Stinson et al., 2013). Educational gamification, on the other hand, has been forced to use a wider range of gamification, as it cannot rely on the promise of beneficial health outcomes to engage participants. Duolingo (Duolingo, 2012) gates more sophisticated language learning behind tests, as participants jumping to a level they are not prepared for has negative outcomes for the participant and the apparent feelings of a lack of competence would not aid in internalising motivation (Gagné & Deci, 2005; Shortt et al., 2023; Wang, 2023). This can be extended to Balance-Land, as Chapter 4 similarly found participants, if given the option, would progress to a level they were not prepared for and experience a negative outcome.

Educational gamification has found streaks to be highly effective at motivation, with participants ranking it in the top 3 motivators for playing (Wang, 2023). Streaks could be a relatively low barrier gamification feature to implement, with the primary requirement being tracking the participant Data. There is the issue that this may motivate participants to play Balance-Land when it is in their best interest not to, such as risk of overstimulation due to a high-symptom day. However, if participant score data is being tracked, the evidence from Duolingo and Chapter 3 indicates feeding back score data to participants would be motivational (Shortt et al., 2023;

Wang, 2023). This would not risk overstimulation, as the participants can wait until they feel ready to push for a high score, rather than every day, and is supported by SDT via increasing feelings of competency and giving participants the autonomy to target the scores they wish to increase (Gagné & Deci, 2005).

During the survey of Chapter 2, the interviews in Chapter 3, and the free responses from participants in Chapter 4, participants highlighted they would all be more motivated to play Balance-Land if there were evidence of rehabilitative efficacy. Regardless of the form, this necessitates the gathering of data from participants on their symptoms, which was previously done outside of Balance-Land itself. This had an issue of tying external participant data to Balance-Land data, additionally with participants occasionally forgetting to fill out their diary. To remedy this, participant data can be gathered internally, meaning participants must provide data for every play session.

Not all motivational forms of gamification can work in the context of Balance-Land. This may be because: some forms of gamification lead to play patterns counter-productive to the rehabilitative goals of Balance-Land, such as score multipliers; others require too much investment to implement, such as sending participants merchandise; or simply due to the users of Balance-Land not resonating with a form of gamification. However, the dropout rate for the feasibility study in Chapter 4 was 45%, which needs to be improved, requiring motivational gamification features be implemented.

In Part 1 of this chapter, the qualitative feedback from the exit interviews of the feasibility study in Chapter 4 will be analysed to answer the following question:

- What engagement features do participants request in Balance-Land?

In Part 2 of this chapter, we will prioritise a subset of these improvements by assessing the feasibility of implementation alongside the potential clinical benefit of the changes. Three changes are then implemented, with initial feedback obtained from clinical users.

6.2 Part 1: The game users' voice

6.2.1 Methods

6.2.1.1 Participants

All participants were asked whether they would be interested in taking part in an exit interview as the final question in the time 2 surveys, for £20 or their currency equivalent. Any participant that responded "yes" was then contacted and offered an exit interview. After a participant accepted, they were given the interview questions in advance, and a virtual meeting was scheduled. If a participant could not attend a virtual meeting, they were offered the option emailing back answers to the questions or corresponding via messages in real-time. The control group were not included for this analysis as they did not play Balance-Land. Participants included are all those from the intervention group that did an exit interview. This leaves 15 intervention participants.

6.2.1.2 Materials

The exit interview was comprised of 15 questions (see Appendix 4). Out of these 15 questions, 8 were of interest to future improvements of Balance-Land related to game modes, environments, or other features:

1. What did you enjoy about the game, if anything?
2. What are your thoughts on the different word games you can play in the game? What games would you prefer in the future?
3. What did you think about the range of virtual environments to choose from (e.g. dessert, forest, supermarket)? Are there any more you would like to see in the future?
4. What would motivate you to play the game more?
5. What sort of feedback do you like to see about your rehabilitation progress in the game?
6. How much control did you feel like you had over how your symptoms were triggered? Did you slow down and speed up or go to different environments depending on your symptoms?
7. Throughout the course of the study, did you change the way you interacted with the game based on your symptoms?

8. How did you decide what environment to play in each day (the desert, the woodland or the supermarket?

6.2.1.3 Procedure

The interviews were targeted to last no longer than 30 minutes. They began with the interviewer confirming all the information that had been sent to them in emails: the interview would last 30 minutes; they would be asked each question sequentially; they may answer in any way they feel relevant, there was no wrong answer. Participants were informed after the 15 questions had been asked and answered they would be given an opportunity to talk about anything related to the study, if there were any questions or comments they had, they would be free to ask. After this, follow-up questions to the 15 original interview questions would be asked, if there was still time left in the interview. Participants were asked whether this format was acceptable and whether they wanted any changes, all participants found the format acceptable. At the end of the interview, the interviewer reviewed how to get payment for the interview with the participants.

6.2.1.4 Data Analysis

The questions were analysed using conceptual content analysis (Elo & Kyngäs, 2008). Comments were initially separated into four broad categories: positive, negative, future, and playstyle. From here, comments were further categorised by the topic of the comment, e.g. gameplay, environment, symptoms. Finally, comments were tallied by the category.

- Positive comments were where participants said anything they liked about Balance-Land, e.g. *"I did enjoy the challenge of making the words"* would be a positive comment about gameplay, specifically about the game mode 'Make a Word'.
- Negative comments were anything that was about an aspect of Balance-Land a participant did not like or felt negatively towards, e.g. *"there were also too many homonyms"* was a negative gameplay comment where the participant was frustrated at having to guess in the "Find a word" game mode.
- Future comments were any comments that wanted a change to happen to Balance-Land, and could be positive, negative, or neutral. For example, *"I would have really like to seen, maybe something kind of to do with the*

commute." Was a future comment about an environment the participant would like to see added to Balance-Land.

- Playstyle comments were any comments participants made that were related to how they played Balance-Land, e.g. *"On harder days, I tended to go to the... I don't know... I was more comfortable in the forest."* Was a playstyle comment on how the participant chose which environment to play.

6.2.2 Results and Discussion

As many of the questions of interest had a component of asking participants what they would like to see in the future, it is unsurprising that most comments were about things participants would want changed about Balance-Land (98 comments). Positive and playstyle comments had 64 comments each. Finally, negative comments were the smallest portion, with only 22 comments. This was to be expected, as most participants that did not like Balance-Land most likely dropped out or refused an exit interview.

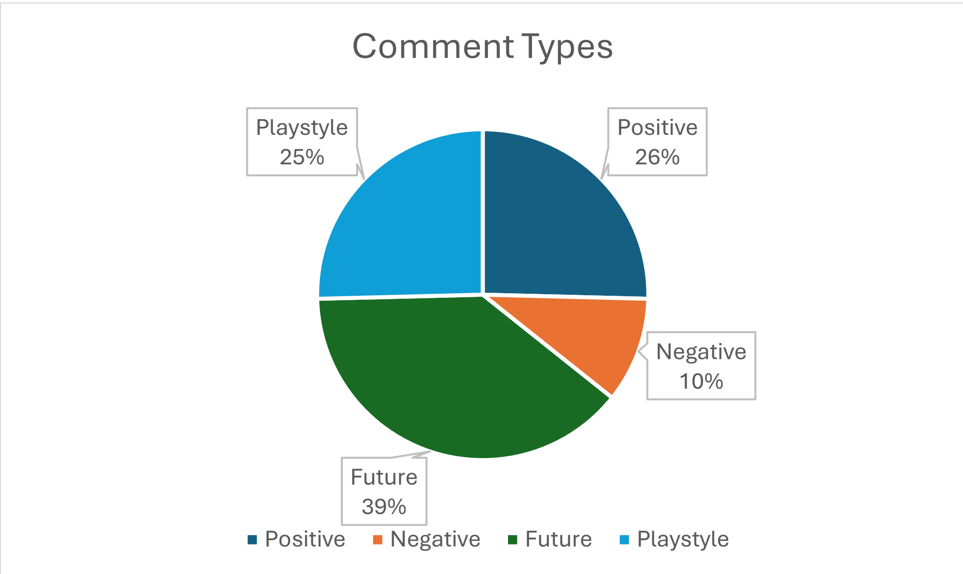


Figure 24, Breakdown of comment types.

Looking further into the future comments, most were about changes to existing environments or ideas for new environments (33 comments), followed by changes to gameplay (28 comments), and finally preferred ways for feedback, which combined gameplay, environment, and symptom feedback (27 comments). There were no comments on symptoms, mainly due to any comments concerning symptoms being focused on how they would prefer feedback on their symptoms and rehabilitation progression, rather than the symptoms themselves. Gamification comments were on ideas participants had on how best to gamify Balance-Land, e.g. score multiplication. The only paradigm comment was a participant requesting Balance-Land become a mobile phone app.

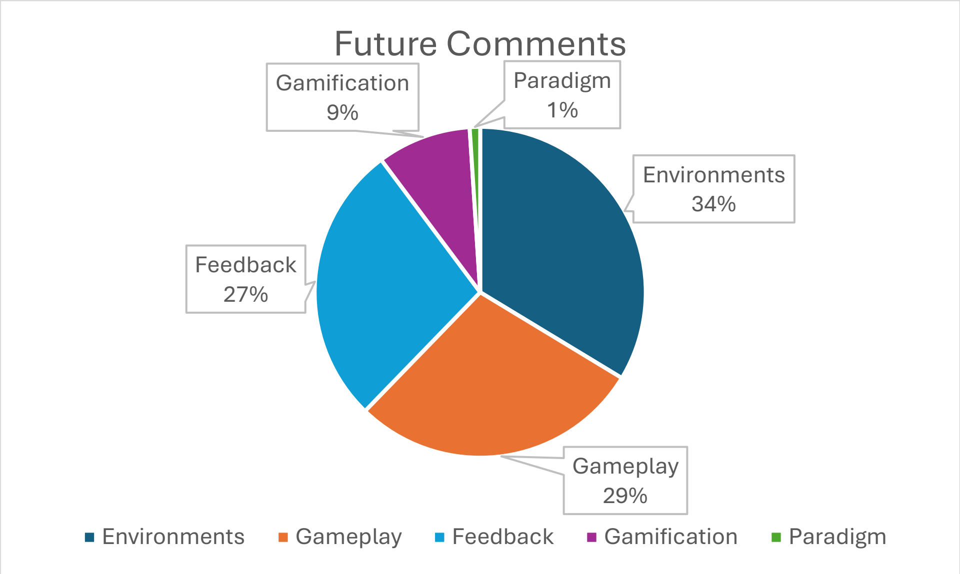


Figure 25, Breakdown of Future comments content.

Positive comments primarily focused on gameplay, due to the first question participants were asked. Environment comments were primarily due to participants naming their favourite environment, or praising the options provided to them. Symptom comments were purely participants praising the level of stimulation provided.

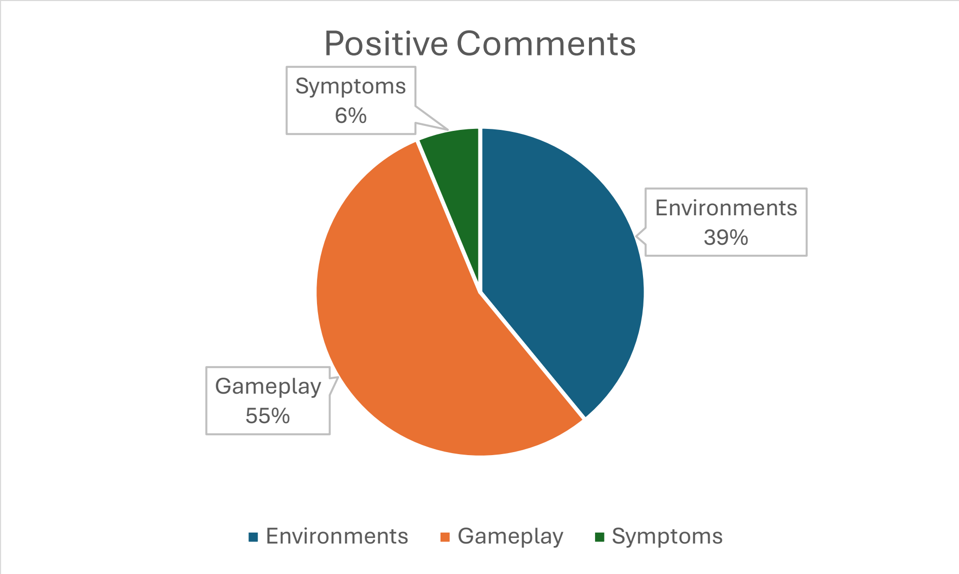


Figure 26, Breakdown of Positive comments content.

Many playstyle comments were about how participants would play with regards to their symptoms, partially driven by the question asking participants how much control they felt they had over symptom provocation, with many citing varying speed and pushing through unpleasant symptoms to finish a game. Environment comments were participants specifically noting seeking out Supermarket to trigger more symptoms, or talking about how they would vary symptoms within an environment to manage their triggers. Chosen environments were all comments about how a participant decided to choose what environment to play, which was mostly due to symptoms (9 comments) or interest (4 comments), with one participant citing randomness (1 comment). Gameplay comments were about what gameplay goals participants set themselves when they played, such as attaining a high score. This was similar to the motivation comments, which focused on what motivated participants to play Balance-Land itself, such as noticing symptoms decreasing over time. Progression comments were about how a participant's playstyle progressed over the course of the feasibility study, with most comments being about how participants followed recommendations to start slow.

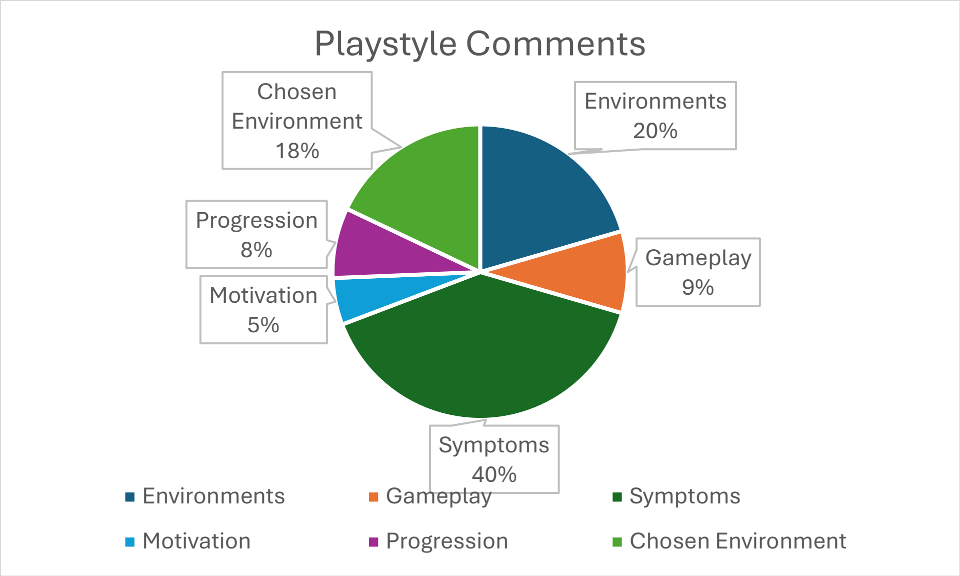


Figure 27, Breakdown of Playstyle comment content.

Negative comments were mostly elicited by frustrations around different gameplay mechanics, or bugs from the game. Whilst some environments were praised due to their difficulty or lack thereof, the same environments were also commented on negatively by others for the same reasons. Symptom comments were participants negatively talking about symptom triggers, either through overstimulation (4 comments) or a lack of stimulation (1 comment).

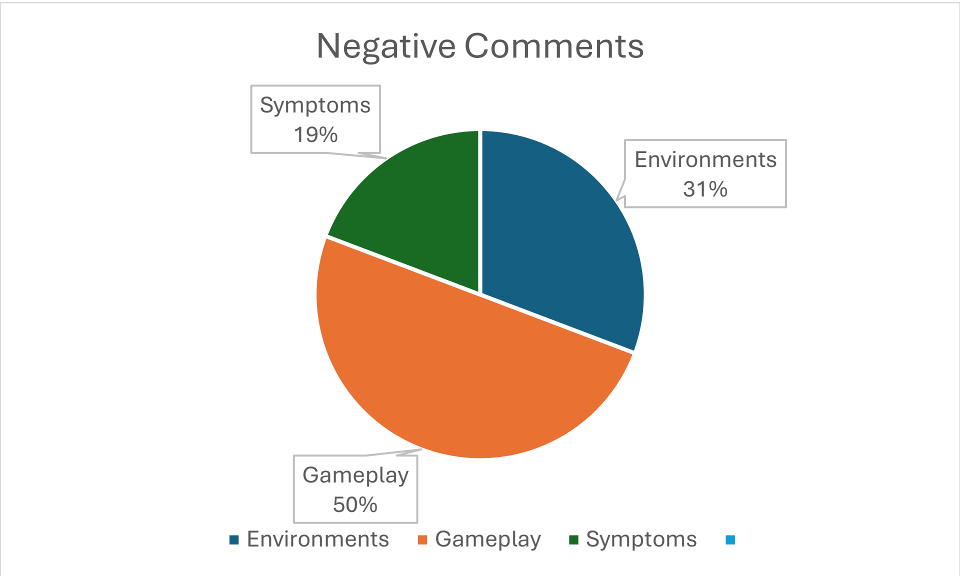


Figure 28, Breakdown of Negative comment contents.

6.2.3 Breaking down the comments of participants

The majority of future environment comments were for street walking (9 comments), malls (4 comments), or some form of commute: the tube (2 comments, meaning underground trains); in a vehicle (3 comments); in a cave or tunnel (4 comments, similar to the tube). The comments implicitly or explicitly implied there would be other forms of movement: "*Supermarket could be made more true-to-life*", "*Perhaps a busy street with cars driving past, that's often a similar situation to the supermarket where there are static items but also items whizzing past*", and "*Moving cars to simulate real challenges*".

This reinforces findings from Phase 2, where participants enjoyed the idea of higher difficulty levels of the environments having the option to incorporate other moving objects. Some participants commented on wanting larger environments (4 comments), but it was unclear whether this was due to wanting more variation within the environment or to make the environments feel more realistic. These give targets for future Balance-Land development when expanding scope, however, new environments require large amount of development time.

Future comments around things that would not require a long development pipeline focused on feedback and gamification, with some comments around quality-of-life gameplay features. The gamification comments focused on getting rewards (3 comments): "*more challenging aspects, like levelling up*", comparing their scores to other's (4 comments), recording the top score of each environment (4 comments), and score combinations (2 comments). Gameplay comments mentioned new game modes (6 comments) in general with 8 comments specifying non-letter games: "*I would do more word games, but those probably come more naturally to me, so I might learn more by trying to find birds*", and 2 comments about reduced repetition for game modes.

Feedback comments were asking for data visualisation (8 comments): "*If you've got metrics you can show me. You know that would be nice*", everyday symptom feelings (8 comments): "*just really, whether over at any time did it Was I starting to feel better. you know, find it easier. Be happier, you know, when you have the faces.*" (referring to the daily diary symptom rating), time to complete a level (5 comments), and movement speed information (3 comments), with participants implicitly assuming completing an environment with a higher mean speed would be indicative of rehabilitation process: tolerating higher sustained visual flow being taken as evidence of desensitisation. However, Figure 29 shows that participant mean speed did not vary across the feasibility study, meaning participants believe this erroneously or the time this would take to manifest is far longer than would be useful for motivation.

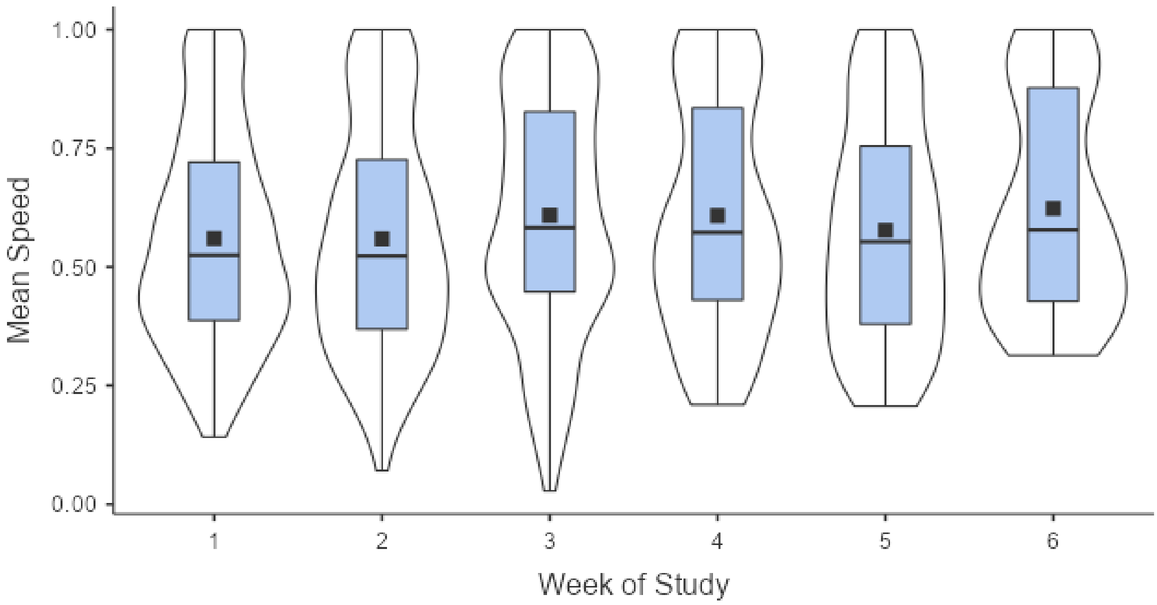


Figure 29, Mean speed percentage across feasibility study week. Black blocks indicate the mean. The blue bar is interquartile range.

Taken together then, the consensus on the most popular new environment was street walking, along with any new non-letter game mode. Participants were insistent they be fed back some data about their symptoms or rehabilitation progression, with time to complete a level and movement speed suggested as proxy scores. Gamification suggestions focused on community-based features where they can get high scores and show them off or compare them to others: essentially a desire for increased relatedness to other participants.

Positive comments had people specifically calling out “Make a Word” as the most popular game mode (11 comments), even though they were never asked to pick a favourite, with 7 comments from participants stating they enjoyed “Find a Word”, and comments for the “Shopping” mode: “*Okay of the make words and the find words I've preferred the make words. I really like that*”. Participants may have felt as if they had more autonomy in “Make a Word”, as they had the freedom to choose which words to make. However, there were notable design differences between the two game modes, with “Make a Word” having more frequent movement pauses and thus less visual flow, along with no failure state. 8 participants expressed positive comments about the range of environment options, with 6 comments mentioning Park as the favourite, followed by 4 comments for Supermarket, and 1 comment for Desert for favourite: “*The range of environments was perfect; I was able to utilize each game based on how I felt. One was easier than the next* “and “*I like that. I could choose the level of intensity*”.

Surprisingly, 4 comments called out the environments for being stimulating in a positive manner: “*once I went to the supermarket, it definitely was more difficult, but I kept going back and forth between the 3”*. Park was the favourite for most commenters, primarily due to the greenery and more open-feeling area, compared to Supermarket and Desert. Participants felt if they were too stimulated in Supermarket, they could always do Park: “*On harder days, I tended to go to the... I don't know... I was more comfortable in the forest*”. The negative comments highlighted 2 participants found Supermarket too stimulating, and 6 found Desert not stimulating enough: “*I couldn’t see any reason to stay in the boring desert on slow*”. 5 participants had negative comments around having to guess in “Find a Word”: “*there were also too many homonyms*”, potentially because there were localisation issues whereby English (United Kingdom) words were utilised and many participants may have learnt English (United States) along with 3 comments on frustrations about unclear options (e.g. B_G could be BIG, BUG, BOG, BAG, BEG).

Gameplay comments showed that 13 of the 15 participants varied their speed in response to their symptoms, utilising one of the intended levers for visual flow: “*I noticed I had the most control over the speed of the game. When I felt symptoms coming on rapidly, I slowed down the pace and it was much easier and I could continue for the time expected*”. 7 commented about wanting to push through negative symptoms, rather than aiming to maintain or mitigate them: “*I think I was too determined, if I'm in this environment. So I’m going to stay there”* and “*with me, if I had a goal, even if I wasn't doing well, I’d still try to meet that goal and then overstimulate*”.

There were 3 participants that explicitly mentioned utilising a coping strategy, which was to look away from the screen: "*I keep it going, but I would look away every now and then*". 9 participants chose their environment to play based on symptoms: "*If my symptoms were poor, I would play Desert which I found the easiest. If I felt decent, I would play supermarket. I felt Park was great middle ground",* and "*I didn't want to always do something super easy when I felt that rough right, and then, when I felt completely fine, something really really hard*", with 10 participants commenting Supermarket was their go-to environment for stimulation: "*supermarkets came under the difficult umbrella for me. That was clearly my go to when I wanted to challenge myself"*. 6 participants commented they varied their gameplay by playing two different environments in one game session.

The largest motivation to play was reported as noticing they feel better (3 participants): "*I think the fact that I do feel better. So that's my biggest motivator*" and going for the highest-point word (3 participants): "*I'm competitive*", with 1 participant noting no effect "*I felt a little more distressed because I hate playing video games, but I gave it my all anyway, until I realized my symptoms weren't budging in anyway"*. Comments about the rehabilitation aspects, such as certain environments being too stimulating or not stimulating enough, were viewed as evidence for differential effects of environments on participant symptom. These comments meant the participants found a differential effect of the environment on their symptoms, which was one of goals of offering different environments. However, some participant comments revealed they went to Supermarket too soon, and with the attitude of "pushing through" symptoms, became overstimulated, which caused them to play less.

There were many more comments than this in the interview, however the purview of this analysis was to determine future changes to be made to improve Balance-Land for the participants and to improve rehabilitation for them. As such, other comments about their symptoms and struggles outside of Balance-Land were not analysed, such as this comment from a participant about how their clinician was dismissive and generally rude, which is consistent with findings by Gamble et al. (2023), echoing the findings that people with visually induced dizziness can feel dismissed and marginalised by their healthcare providers:

"I suppose he looked at imposing, I suppose, like a really threatening butler, you know, really tall, and he's really lucky. I'm a very i'm kind of a pacifist. But if his window had opened I would have pushed him out it."

6.3 Part 2: Prioritising and implementing key improvements

6.3.1 Building a list of potential features

Balance-Land must be continually improved, but not all the features require the same effort to implement or have the same interest from participants. To this end, the comments from participants were then categorised into potential features (e.g. new game mode) that could be added to Balance-Land. Each feature had the level of interest expressed by participants calculated, the feasibility of implementing the feature estimated, and the clinical need of the feature assessed. The level of interest is how much support from the participants a feature has, and the clinical need is based on whether a feature would directly aid in rehabilitation.

To assess the level of interest of a feature, the suggestions from participants were categorised into the underlying feature and then tallied. For example, requests for a commuting environment or a driving environment both counted towards a "new environment" feature.

After categorising the features and assessing the level of interest around them, the feasibility to implement the feature was estimated. Feasibility was ostensibly broken down into two categories: the time investment needed for the feature and the cost investment for the feature. This was expressed by categorising either of those two categories as low or high, and expressing the overall feasibility as a combination of them: low and low created a highly feasible feature; low and high created a moderately feasible feature; and high and high created a non-feasible feature.

Assessing the clinical need of a feature request was done by evaluating whether the feature would aid in the rehabilitation potential in any way. If yes, there would be a clinical need for the feature. For example, new environments would have a clinical need as provide additional visual desensitisation stimulation, and potential anxiety reduction, whereas new game modes would not have a clinical need as they do not directly impact visual desensitisation or anxiety, only engagement (see Table 4).

Table 4, Feasibility, clinical need, and level of interest from identified features. Bold features were selected to implement.

Feature	Feasibility	Clinical Need	Level of Interest
Game mode	Low	Low	High
Environment	Low	High	High
Feedback	**High**	**High**	**High**
Overstimulation	**High**	**High**	**Moderate**
Phone App	Low	Low	Low
More visual options	Low	High	Moderate
Aptitude tracking	High	Low	Moderate
Community leaderboards	High	Low	Moderate
Rewards	Moderate	Low	Moderate

6.3.2 Choosing features

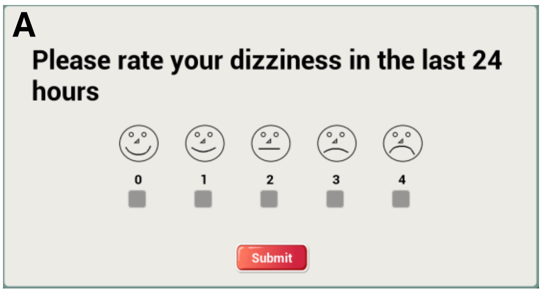
Features were prioritised based on feasibility, followed by clinical need, then level of interest. Any feature not considered for implementation will be returned to later, in Chapter 7 (General Discussion). Any feature with a low feasibility assessment was not considered for immediate implementation. Next, any feature with low clinical need was not considered. Finally, features were rated by level of interest. As a result, feedback to participants about their symptoms and options to limit stimulation were the most feasible features to implement.

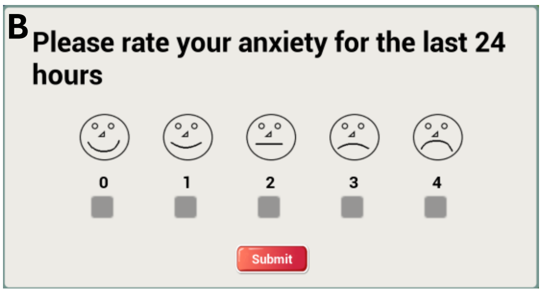
Additionally, since feedback to participants necessitates setting up, securing, and tracking participant game data, this can be used for other purposes in future. For example, the barrier to tracking game-related scores (such as total score gained) is now lower. This then allows for easier development of community-based leaderboards for future gamification or even ability-based rewards in the future. It must be noted that data gathering comes with security concerns around participant data and long-term data storage, such as the General Data Protection Regulation (GDPR). However, data storage for the participant data from Chapters 2, 3, 4, and 5 already comply with Cardiff University Data Protection guidelines (which are GDPR compliant), meaning future data can be stored securely in the same manner.

6.3.3 Feedback

To feedback information to participants on their symptoms, Balance-Land must be able to track unique users and tie the data to them, gather the relevant data to feedback, then store and retrieve this data. To track unique users and tie the data to them, the decision was made to force participants to make a user account with a username, e-mail, and password, rather than relying on participant ID codes, as was used throughout the feasibility study. As a solution, this has been utilised extensively through-out software use, with participant data still being securely stored on a protected server. Any data the participants provide is now tied and stored to their account, rather than the study ID that was previously utilised in Chapter 4. This then lets Balance-Land query and show all data relating to an account upon request, with Figure 30D, 30E, and 30F demonstrating different variants of the same participant data.

The stats screen was available from the bottom right of the “Select Game Mode” screen (see Figure 30C). Clicking on this will show Figure 30D, which feeds back the mean of the participant’s ratings for the last 4 weeks. Buttons in the bottom left can then additionally present this data over the last week (Figure 30E) or the last 8 weeks (Figure 30F). The goal of showing participants their data over various time-points was to hopefully motivate participants by allowing them to view small decreases. However, this may have the opposite effect of demotivating if participants consistently report increasing scores. Participants can also check if they had a particularly poor day within the last week.





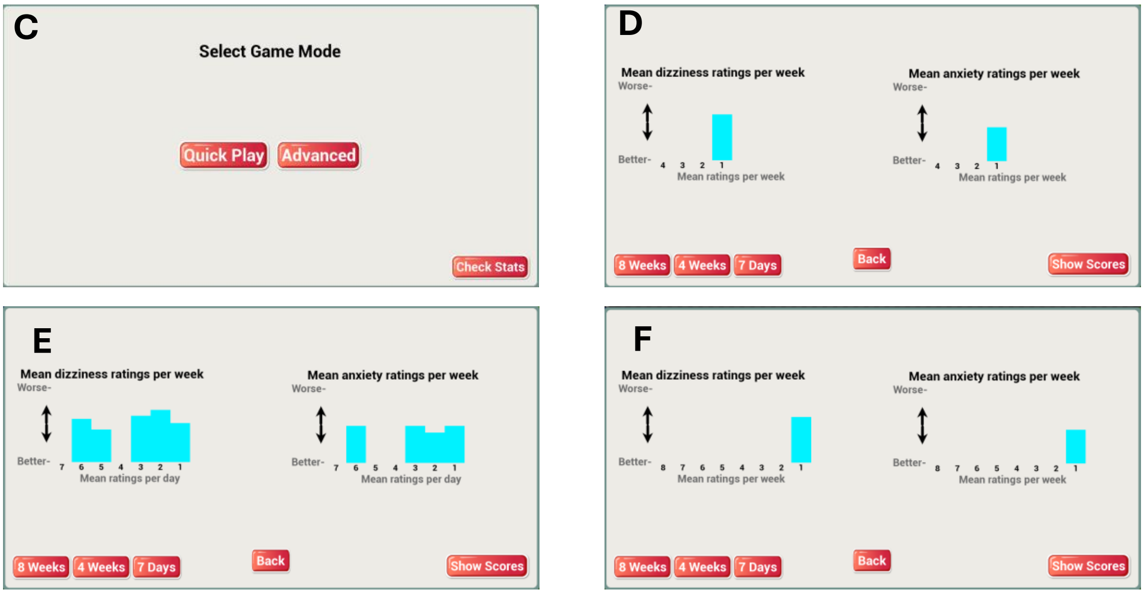


Figure 30, Screenshots of Balance-Land showcasing data collection and visualisation.

Many of the common visually induced dizziness questionnaires are self-report, such as the VVAS (Dannenbaum et al., 2011), the DHI (Jacobson & Newman, 1990), or the NPQ (Yagi et al., 2019; Yagi et al., 2021), and clinician feedback from Chapter 3 had 5 of the 6 clinicians stating some form of self-report measure as sufficient to show rehabilitative efficacy. Participants also responded well to the self-report daily diary ratings in Chapter 4's feasibility study, with pre-play ratings being correlated to active playtime and the only known issue being participants forgetting to fill out the diary. Therefore, to preserve the beneficial aspects of the diary ratings and solve the completion issue, the daily diary rating was converted to a 5-point Likert scale and embedded within the game start pages (see Figure 30A).

Anxiety is an important component of visually induced dizziness rehabilitation (Staab, 2023; Staab et al., 2017; Trinidade, Cabreira, Kaski, et al., 2023) and some participants mentioned noticing anxiety differences, supported by the time played and HADS-A subscale correlation in Chapter 4 and 5 of 6 clinicians in Chapter 3 prioritising anxiety reduction as much as symptom reduction. As such, an anxiety-based 5-point Likert scale was added (see Figure 30B).

To solve the issue of non-compliance, participants are not given a choice on whether or not to fill these questions out. A response much be given for each scale before progressing to play Balance-Land. This adds a minimum of 4 left-clicks before playing, once on each scale to select a response and once each on each scale to submit a response. This does not seem an undue burden to participants, but feedback and play patterns will be checked at a later date to ensure this.

6.3.4 Overstimulation

Two participants from the feasibility study in Chapter 4 gave too much stimulation as a reason for dropping out, along six participants in the exit interview specifically commented that Desert was under-stimulating and two that Supermarket was too stimulating. Participant data revealed that many participants did not read instructions, for example many participants played Supermarket as their first environment despite numerous written instructions to not do this, along with prior research also a similar issue due to participants not reading instructions (Beltran et al., 2012). This, taken with prior the prior comments, implies that there were some participants that did not read instructions, played Balance-Land, found Balance-Land too stimulating, then immediately stopped playing.

Participants engaging in unintended behaviour links to one of the original goals of Balance-Land: do not let a participant rehabilitate improperly. As such, this had to be remedied and was done so by extending the above stat tracking. Now, participants have the score recorded from each environment, now requiring 100 points, equivalent to one successful play session, on the prior environment to unlock the next. For example, 100 points on Desert is required to unlock Park, and 100 points on Park is required to unlock Supermarket. Participants can view their progress at any time in the stats page (see Figure 31A) or by simply playing the game (see Figure 31B). The decision to initially make the threshold 100 points, or one successful play session, was because all participants in Chapter 4 stated they knew the controls by the end of one play session. This should strike a balance between stopping overstimulation and not erecting a large barrier for those participants that need more stimulation than Desert or Park may provide. The threshold will be reviewed through user feedback.

Participants can check their unlock progress at any time by starting the game, or by checking their scores in the “check stats” screen (Figures 31A & 31B). The scores in the “check stats” screen show their lifetime scores, with an aim to encourage participants to get a high score, with four participants wanting to see their scores for each environment, and four stating they played to improve their scores. This can easily be expanded in the future to include longest word, highest scoring word, et cetera, for gamification purposes.

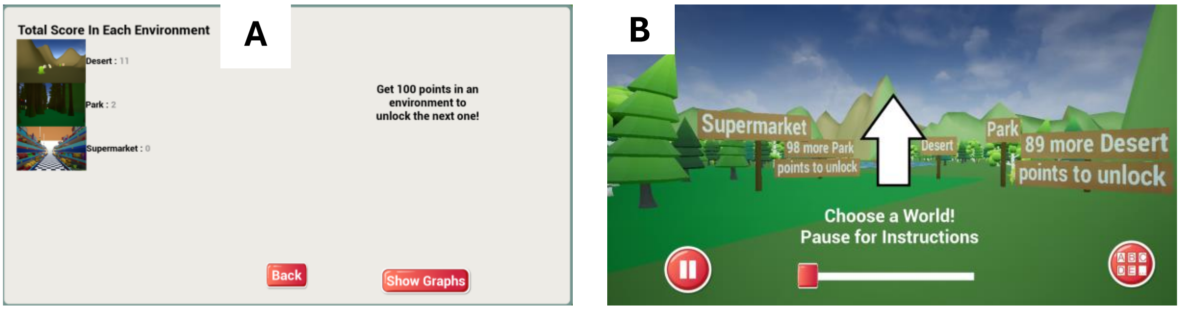


Figure 31, Showing total scores in each environment (left) and what a participant sees when they need to unlock environments (right).

6.3.5 Clinician Feedback

The six initial clinicians from Chapter 3 plus two clinicians that aided with the feasibility study in Chapter 4 were contacted about offering feedback on Balance-Land after the latest round of changes. Of these eight clinicians, two clinicians responded and were offered structured interviews to assess their thoughts on the final changes to Balance-Land. The structured interview was comprised of 6 questions:

1. On the start-up page, we have included a scale for participants to rate their symptoms and anxiety. We are aiming for simplicity, so that ratings are provided every time they play in order to keep a record for the participants themselves and potentially clinicians. Could this be phrased or presented in a better way?

2. We currently feed the mean of these scores back in the “stats” page, averaged over weeks, for example. Do you think this is the best way to feed back the information? For example, we would not necessarily expect a drop in ratings in a week yet provide this option as viewable, which may lead to a loss in motivation rather than a gain?

3. Should we be explicitly asking participants any other questions? Note that we do not want to disincentivise rehabilitation by asking for too much.
4. We currently ask participants to rate scores once at the beginning of play. Do you recommend having ratings after each environment? (Note again the balance between simplicity and more information).
5. We now block participants from going straight to the more stimulating levels – Park and Supermarket. They have to score 100 points in Desert to open the Park, and 100 points in Park to open the Supermarket. 100 points can be gained in one successful game of about 10 minutes. Do you think this is sufficient or should this be extended?
6. Should any other features be gated behind an unlock?

After doing conceptual content analysis on the responses from the clinicians (Elo & Kyngäs, 2008), both clinicians present similar feedback for the intention of the features: the changes are good but can be improved. Both clinicians think rating dizziness and anxiety before playing is a good idea "*this is important to have*". Both clinicians think feeding back information to participants on their dizziness and anxiety is "*definitely helpful*".

On the locking of content, the clinicians were in disagreement, with one viewing this feature as "*critical…it should be extended*" and the second thinking the necessity of locking "*will vary on the individual*" and expressing Balance-Land "*recommend doing [Desert] 'a number of times' before progressing*". However, data from Chapter 4 demonstrated participants were instructed exactly as a clinician recommended and the result was participants ignoring the recommendation and overstimulating. One clinician suggested introducing a post-play symptom rating, similar to the diary in Chater 4, and tying environment unlocks to this rating. Ensuring the participant is not overstimulating, that is, only a 1–2-point increase from playing, would unlock the next environment.

When looking at the implementation of the features, instead of the intent, the clinicians have many suggestions. Both clinicians have suggestions on how to improve the before-play symptom and anxiety ratings, with the intent of ensuring the participants rate relevant symptoms, such as "*anxiety about your dizziness*" rather than purely anxiety. This extends to the information being fed back to participants, as the purpose of presenting this information is for participants to understand their symptoms and progress. Both clinicians agree the graph labels can be improved for more clarity, with one suggesting a disclaimer "*These exercises take time and commitment to work! It is completely normal not to see any improvement in your scores for the first xx weeks*". This would alleviate the identified concern of demotivation if participants do not notice an immediate decrease in symptom ratings. Finally, one of the clinicians suggests moving ratings to before playing an environment, rather once at the start of a session, to be better able to capture the effect of each environment on the participant, when combined with post-play ratings.

6.4 Discussion

The original research goal of the PhD was to find a minimum path for impact for a new rehabilitation tool. This was expressed via three goals:

1) Adherence: participants must play Balance-Land for there to be an effect.
2) Rehabilitation potential: Balance-Land must have rehabilitation potential.
3) System Usability: Balance-Land must be useable to all participants.

The final changes to Balance-Land were aimed at better hitting engagement for participants to improve adherence, whilst not detrimentally affecting rehabilitation potential or usability. Participants may view their mean symptom and anxiety ratings, allowing participants to see their progress, providing motivation and engagement. This in turn means that Participants now must provide information on their symptoms and anxiety once per play session, to provide feedback and increase motivation. It is currently unknown if usability will be affected by this change, but every effort was made to ensure the minimum of time and effort is required from the participant to progress to playing Balance-Land, as shown by only requiring 4 left-clicks to progress. Ensuring all the new features only require left clicks keeps the option for future development into the mobile phone app space, which was requested by one participant during the exit interviews along with other users in Chapter 4.

Feedback from the clinicians support the general idea behind the changes: they were all in the correct direction to positively affect participants that play Balance-Land. The major point of contention was behind the unlocking of environments to allow progression rewards and prevent overstimulation. One clinician preferred the direction of the feasibility study in Chapter 4, which unfortunately leads to negative participant outcomes. The other clinician suggested tying unlocks to after-play participant symptom ratings. This suggestion appears to be a better solution than the one implemented, because this would ensure only participants that do not overstimulate can progress. However, this could require that participants would not be informed as to how to progress, otherwise participants would simply misrepresent their symptom rating, defeating the point of the change. This lack of information might introduce frustration. Alternatively, one would have to rely on the participants understanding that it is best to be honest about their symptoms and not to progress too quickly. The only other barrier would be participants rating their symptoms a second time.

The change to requiring participants to register an account and provide an email address leads to the possibility of improved motivation. Previously, only limited data was able to be accessed easily due to the anonymisation of information.

There is a small risk that some participants instead see an increase in symptom ratings, which may then lead to demotivation. The suggestion from the clinicians provides a solution to this: warn participants they should not see immediate effects, and to contact their clinician if they have concerns over the effect Balance-Land is having on their symptoms. Additionally, participants will be able to share their daily information with clinicians, which should improve the care received.

6.5 Conclusion

Participants now log into Balance-Land via username or e-mail and password. Additionally, participants rate their symptoms and anxiety in Balance-Land itself, rather than externally, and may view their aggregate scores whenever they desire, including sharing them with clinicians. Feeding back symptom and anxiety information allows participants to see progress when they may feel as if Balance-Land was not helping, which directly targets the most consistent feedback from participants since Phase 1 in Chapter 2: participants would be motivated if there was evidence Balance-Land affected their symptoms. Clinicians have confirmed the rationale behind the changes are positive for participants, but the implementation can be improved. Further gamification elements can be more easily included in the future, which will be discussed in Chapter 7.

7 Chapter 7: General Discussion

7.1 Overview of findings

This thesis aimed to create a novel form of visual desensitisation rehabilitation that solved the identified issues of motivation and rehabilitation accuracy found in the literature, whilst remaining customisable for participants of varying symptom severity. Balance-Land was realised as a web-based form of intervention and as a piece of software must be useable by participants resulting in a third goal of high useability.

Balance-Land has gone through many iterations through the course of development. In Chapter 2 Balance-Land was piloted on BabylonJS and the initial feedback from participants indicated the design goals of motivation, accessibility, and rehabilitative promise were being partially met: participants reported moderate symptoms; over half found the controls easy to use and pick up; some participants found gameplay fun; and there were comments about how Balance-Land positively affected anxiety.

From this feedback, in Chapter 3 Balance-Land went through multiple design iterations, taking on-board feedback from people with visually induced dizziness and vestibular clinicians. Balance-Land development was shifted to Unreal Engine and the feedback from participants in Phase 2 shifted Balance-Land to becoming a full world environment rather than procedurally generated, along with the Find a Word game mode. The user interface was redesigned to be simpler, more responsive, with clear feedback, and the result was high SUS scores indicating high usability. Participants confirmed symptom evocation was caused by Balance-Land and maintained a moderate intensity and provided many ideas for future development avenues. These changes better fulfilled the goals of accessibility and rehabilitative promise than Chapter 2, with the new game mode improving motivation.

In Chapter 4 a feasibility study was conducted after implementation of a third game mode, Shopping, from Chapter 2 feedback. Participants from all over the world were invited to play twice daily for 6 weeks. We found Balance-Land active playtime was correlated significantly with visual vertigo analogue scale score reduction, along with the hospital anxiety and depression score reduction, providing evidence Balance-Land might be used to rehabilitate people with visually induced dizziness. However, we also found that there was a 45% dropout, resulting in a large self-selection bias. This means there is evidence Balance-Land works as a tool for visual desensitisation rehabilitation and is globally accessible, but participant motivation can still be improved.

Chapter 5 investigated the different factors that may have affected playtime and the relative symptom increase of participants. We found that the week a participant played in significantly affected their relative symptom increase, indicating participants became desensitised throughout the course of the feasibility study, which is the goal of visual desensitisation rehabilitation. We also found the symptom duration from the last time a participant played Balance-Land was a positive factor for playtime, which was surprising. This indicated participants either employed coping strategies, formed habits they were unwilling to alter, or both. However, the factor itself was tiny (0.006), along with the linear mixed model being small (R_c^2=0.09), most likely meaning there is another, larger, unexamined factor. These findings partially explain how Balance-Land works as a tool for rehabilitation, encouraging consistent use of Balance-Land, which in turn will motivate participants to play more.

Finally, in Chapter 6 changes to Balance-Land were made to improve engagement via gamification from the exit interviews of the feasibility study. Participants are given feedback on progress with their symptoms and their game achievements. To enable this, they must now self-report their symptoms and anxiety before playing, solving the poor diary adherence in Chapter 4. The issue of overstimulation, where participants go to Park or Supermarket and trigger intense symptoms, was solved via gating. Participants must now play Desert at least one and subsequently Park at least once before they may access Park and Supermarket, respectively. This allows participants to understand the gameplay and controls, which, from Chapter 4 feedback, all participants said they understood by the second session. The final change was to require an account with an email address to play Balance-Land and tying participant data to their account. This sets the stage for future community-based gamification options along with opening the door to email reminders to increase adherence. These final changes were aimed at increasing motivation, with all the changes being desired by the clinicians asked. The changes should not negatively affect rehabilitation or accessibility, resulting in Balance-Land achieving all objectives: rehabilitation, accessibility, and motivation.

7.2 Theoretical Implications

Balance-Land was a purely visual rehabilitation tool and made use of visual desensitisation. The diary data from Chapter 4 indicated over 80% of participants did not do any other form of vestibular rehabilitation. As such, the findings of this thesis provide correlational evidence that visual desensitisation rehabilitation in isolation may be sufficient for symptom reduction. However, there was not enough evidence to conclude Balance-Land worked purely through visual desensitisation. The findings from Chapter 4 indicated that symptom reduction and anxiety reduction were correlated with active play time, but there was no indication whether one caused the other, or whether both were affected by Balance-Land. That is to say, Balance-Land could have had a primary effect on anxiety, which then affected the participants' symptom intensity, vice versa, or both were independently affected. Unfortunately, due to being unable to untangle how Balance-Land interacted with the observed symptom and anxiety reduction, we are unable to conclude whether the evidence in the thesis supports the theory of visual dependence, but neither does it not support the theory of visual dependence.

Throughout the course of the entire thesis, there were many participants with persistent postural perceptual dizziness (PPPD) (Staab et al., 2017). However, this was a plurality, not a majority: most of the participants recruited in Chapter 4 did not have a PPPD diagnosis. The most common diagnoses after PPPD in Chapter 4 were vestibular migraine, Meniere's Disease, and vestibular neuritis. Balance-Land did not exhibit a diagnosis effect and appeared to rehabilitate symptoms of visually induced dizziness across diagnoses. This opens up a broader question in the literature, whether the approach of treating symptoms of visually induced dizziness in different diagnoses as separate is the better way of approaching the issue of rehabilitation. However, the coping strategies employed by participants throughout the thesis may have affected how participants responded to Balance-Land, as it is not known if all elements were equally used in rehabilitation. Due to this, it is unclear which factors were driving any observed changes, as the only evidence found in Chapters 4 and 5 were time-based. This is unsurprising, as the primary purpose of the thesis was the practical implementation of a novel form of rehabilitation, with any theoretical findings as an additional benefit.

7.3 Practical Implications

Balance-Land was intended as a widely accessible form of visually induced dizziness rehabilitation and as such has many practical implications. The first, and most important, is that Balance-Land appears to be a viable form of rehabilitation and is currently being utilised by some clinicians in the United Kingdom to treat patients. This is because Balance-Land has achieved its goal of being a low-cost low-barrier tool for rehabilitation, with the only major question being whether the observed effectiveness of Balance-Land was due to the observed self-selection bias or not.

With Balance-Land being used as a rehabilitation tool, this allows for many possible future research opportunities on visually induced dizziness. Changes to Balance-Land made in Chapter 6 mean all people using Balance-Land do so through Cardiff University Dizzy Lab's (CUDL's) website and sign up with their email address. These people can be asked whether they would like to be contacted about future research opportunities or whether they would consent to their data being used for research purposes. More research participants are obviously beneficial, and the participant data can improve usability and potentially linked to other data for improved gamification and rehabilitation changes.

Balance-Land players now have to self-report symptom and anxiety ratings before playing due to the changes in Chapter 6. This can be directly fed back to clinicians to provide more information on rehabilitation, along with automatically recording participant adherence to rehabilitation. These two factors should streamline the patient-clinician interaction and allow for more time to be focused on more relevant issues during any consultation, hopefully resulting in better patient satisfaction, if not better rehabilitation.

When Balance-Land was conceptualised, there was a heavy focus on practical implementation. This can be seen throughout the thesis with the heavy emphasis on user-centred design (Abras et al., 2004) and iterative feedback. The wider literature agrees, with research recommending a focus on practical implementation (Proctor et al., 2011; Smith et al., 2023). In fact Proctor et al. (2011) recommends focusing on eight implementation outcomes, of which Balance-Land has aimed to meet all eight by focusing on real-world implementation. Notably, the feasibility study in Chapter 4 only had 45% dropout, better than other similar forms of rehabilitation (Pavlou et al., 2013), whilst participants were instructed to not change their daily routine and that there may be no effect from playing Balance-Land. This should mean any other experiment conducted with Balance-Land should have a naturally lower dropout rate, as there is evidence of efficacy. Additionally, the recommendations of Bauer et al. (2015) for a multi-disciplinary team were followed with psychology and computer science researchers forming the project, with vestibular clinicians advising on Balance-Land and sought out for feedback in Chapters 3 and 6.

7.4 Revisiting Design Guidelines

In Chapter 3, design guidelines were developed as a result of three phases of user-centred feedback. After gathering more data from Chapter 4, Chapter 5, and Chapter 6, they ought to be revisited and updated. The design goals remain to provide participants flexibility over intensity of therapeutic stimulation, allow access participants access to virtual worlds that they fear in the real world, and a decoupling of gameplay controls from therapeutic stimulation.

7.4.1 Rehabilitation

Chapter 3 found Balance-Land elicited moderate symptoms of visually induced dizziness. This finding was maintained in Chapter 4, but with a large self-selection bias. Whilst the largest single reason given for dropping out in Chapter 4 was due to participant health, at least one participant dropped out due to overstimulation. There were two main paradigm shifts between Chapter 3 and Chapter 4: graphics were made less realistic, to be more widely accessible to participants with less powerful computers; and Supermarket was added to Balance-Land. Graphics becoming simpler would reduce the amount of visual complexity on the screen, which leads to the probable conclusion that Supermarket was likely a factor.

Supermarket involves all the key elements that that are characteristic of visually induced symptom triggers: high contrast, visual complexity, and (optional) high speed motion (Bisdorff et al., 2015). As a result, participants have been stopped from immediately playing Supermarket, meaning they have time to adjust to how stimulating Balance-Land can be. This has the downside of delaying (but only slightly) treating the anxiety-related symptoms of experiencing an environment, noted as a positive in Chapter 3. A longer-term solution would be to offer more low-intensity options in Supermarket, meaning a participant may, after learning the controls, practice in an environment they want to feel more comfortable in or not.

One of the most requested new features in Chapter 6 was for a new environment, specifically with optional moving objects. The most common example would be a commute to work, either via car or train, which would involve other moving cars or people, respectively. The participants giving this feedback were the ones from the feasibility study, meaning the data already provides evidence of rehabilitation potential for this group. It is unclear whether including more stimulating environments would make Balance-Land more effective for rehabilitation, and, as previously noted, risk that the participants would overstimulate. There is a secondary concern some participants withdrew from the feasibility study due to lack of stimulation from Balance-Land, reinforced by participant comments in Chapter 6 finding Desert not stimulating enough. However, if Balance-Land was unable to evoke symptoms in these participants, that means there are existing options for them to rehabilitate with.

This results in the updated guidelines:

- Participants must be constrained to play low-level stimulation environments before progressing to more intense levels, with graded exposure to each type of symptom trigger, so they can determine which types they are most susceptible to.
- Where virtual environments incorporate many of these different types of symptom triggers, some should be optional, to allow participants to maintain symptoms at a tolerable level (e.g. camera roll and shifting were optional and only some participants reported using them).
- Virtual environments that more closely resemble real-world environments have more reports of anxiety reduction and play time. Care must be taken making changes to them.
- Participants find motion along fixed paths more unpredictable than the game designer; for example, they do not know it is impossible to fall off a path. This implied possibility is anxiety-producing and should be avoided.

- Participants try to minimise symptom triggers with coping strategies, which leads to a desire for more triggering environments. This can be achieved by putting in more symptom triggers, or alternatively, should be achievable through gameplay alterations that force retinal movement. Coping strategies cannot be fully removed, with in-game education to participants about their symptoms likely a better solution than making changes that negatively impact game experience.

7.4.2 Usability

Usability was a key research objective. Balance-Land must be accessible by a wide range of people, even those with no video game experience. Data from Chapter 4 was gathered from a wide range of people all over the globe. Many of these people did not have English as their first language, with 6 using a computer less than twice a week. However, participant interviews had every participant responding they knew what every button did and understood all the controls, usually within the first session, and all by the second session. None of the participants reported framerate dips, or other graphical glitches, except those accessing Balance-Land via mobile phone or iPad, which Balance-Land is not currently designed to run on. This data indicates that Balance-Land is highly usable, accomplishing the research objective, supported by the high SUS score.

Chapter 4 indicated Balance-Land had rehabilitative potential, even with the graphical downgrades chosen due to usability constraints. Participant comments from the exit interview still indicate that more realistic, graphically and thematically, environments are more desirable to participants than less realistic environments. This means optional graphical improvements can be added to Balance-Land for the participants that have computers capable enough, given that the lower-level graphics proved sufficient.

As opposed to having an in-game tutorial, which occurred during Chapter 2, instructions were moved to external video-based instructions with salient prompts or reminders within Balance-Land itself. There were links to these videos in Balance-Land, but moving forwards integrating a video player into Balance-Land may be a more optimal solution. This would stop participants needing to open a new tab or change their web page. All actions in the game came with immediate visual and auditory feedback: buttons would make a sound and change colour; tiles would disappear and chime; word submissions had a positive and negative sound-effect. These usability changes maintained usability ratings with a larger and more diverse cohort and was rated in the 80th percentile (Lewis & Sauro, 2018).

This results in the updated usability guidelines:

- Typical users with visually induced dizziness may have very little-to-no game experience. This means avoiding complex or reaction-time based controls, and anything in the game should have immediate feedback and a clear purpose.
- Typical users with visually induced dizziness may have old or low-spec hardware, and thus processing requirements need to be minimised (e.g. using low-polygon graphics).

7.4.3 Engagement

Encouraging participants to play consistently can be done via engagement rewards, which have been found to be beneficial, such as Frommel and Mandryk (2022) who found daily log-in incentives helpful and encouraged their participants to try out different ways of interacting with their chosen game. This could be adapted and integrated into Balance-Land, such as: increasing the points required per level but giving a bonus if words fell into a category (e.g. fruits); asking participants to “play 3 Make-a-Word games”; or even “Play the Supermarket with an average speed of 50%”. Having these sorts of engagement aspects can also alleviate enjoyment or fatigue concerns by encouraging participants to interact with Balance-Land in a different manner. Frommel and Mandryk (2022) highlighted negative aspects that can come with these, although these were related to the feeling of missing out.

A feeling or fear of missing out functions whereby a person perceives they will miss out on something, in this case lose a daily log-in reward, and a compulsive behaviour to maintain (Gupta & Sharma, 2021). Typically, this can create a situation where a person has lower need satisfaction, mood, and life satisfaction (Przybylski et al., 2013), all of which Balance-Land is not intended to cause. However, participants should be playing Balance-Land every day as part of their rehabilitation (as per available data), so incentivising this would be less detrimental than it would for a traditional game. Feedback from participants has been amendable to the idea of community incentives, meaning participants can mutually compete and support each other (see Chapters 3 & 4), which naturally leads into the possibility of community daily play streaks, or other achievements such as longest word made, or highest point word.

The dropout rate of participants in Chapter 4 was 45%, which was better than other experiments involving visual desensitisation (Pavlou et al., 2013). Some of the participants were motivated because they noticed an effect of Balance-Land on their symptoms. Comments from participants during Chapter 6 revealed most participants enjoyed some aspects of Balance-Land, in-line with prior research (Chesham et al., 2017; Salmon et al., 2017). The most notable reasons for non-engagement were: time constraints, overstimulation, and boredom. Overstimulation has been effectively solved, via unlocking environments. Time constraints have a likely solution close to implementation, with email reminders as a potential solution. Boredom varies greatly between participants, but there was a solution mentioned in Chapter 3 and in Chapter 6: community-based scores. These scores should provide some motivation to participants, but care must be taken that they do not lead into any gameplay patterns that create ludonarrative dissonance (see next section).

This results in the updated engagement guidelines:

- Gameplay enjoyment is secondary to rehabilitative benefit but must be engaging enough to retain participants until rehabilitative benefit can be shown; low-polygon graphics and basic gameplay was sufficient to provide a moderately enjoyable game experience that patients reported as preferable to current rehabilitation exercises and has evidence of symptom reduction.
- Participants report high scores, progressing through difficulty levels, and community ties as effect forms of motivating engagement.
- Participants enjoy progressing through levels but will employ coping strategies to do so, giving a false sense of progression. Tying symptom triggers to the gameplay of higher difficulties can ensure participants still receive rehabilitative benefit whilst progressing.
- Participants want a variety of gameplay options but do not want locked-in time commitment. Keeping the gameplay loop close to 5-to-10 minutes appears ideal and sufficient for rehabilitation.

7.5 Limitations and Future Directions

7.5.1 Future Gamification

We do not currently know whether participants in Chapter 4 did not notice any rehabilitative effect, and therefore decided to drop out, or whether any participant that played for a sufficient length of time could get similar results to the participants that stayed. This question would best be answered by a randomised control trial (RCT) (Grossman & Mackenzie, 2005; Meldrum, 2000). However, there are other ways of encouraging people to play Balance-Land more.

In-game rewards have been utilised for player engagement. Before looking at what rewards may work, the goals of Balance-Land must be reviewed, so the proper play-patterns are rewarded. The best way of doing this is through the lens of Ludonarrative Dissonance, first mentioned by Hocking (2009). Ludonarrative Dissonance can be viewed as when the gameplay elements and rewards (the "ludic") diverge from the story (the "narrative") (Hocking, 2009). Balance-Land currently has no story or narrative, which is a possibility to increase engagement as shown by Breien and Wasson (2021), but there is an over-arching goal of getting the participant to experience complex visuals and visual flow for 5 to 10 minutes twice daily: the rehabilitation is the "narrative". As a result, any of the implemented ludic elements must conform to this goal, rather than against it (creating dissonance). For example, a participant feeling "forced" to play every day would not be considered a dissonance when the participant is meant to be doing daily rehabilitation, as this ludic element reinforces the narrative.

Unfortunately, many gamification suggestions from participants in Chapters 4 and Chapter 6 would create ludonarrative dissonance and ultimately undermine the rehabilitation potential of Balance-Land. The idea of recording or incentivising the fastest game time would exacerbate the current problem of coping strategies, whereby participants would be encouraged to move at a faster speed and then not engage with the complex visuals, directly against the goal of Balance-Land. This issue can be extended to other frequency suggestions, such as "Complete X games", whereby the most optimal strategy becomes to utilise speed and clicking on everything in sight with no active visual discrimination. Compare this to a score multiplier for specific word types (e.g. "fruits"), which would decrease the time a participant spent playing, which goes against the goal of getting participants to play for a specific time. Alternatively, participants could compensate by playing additional games, or by increasing the score to complete a game. However, not all players would utilise the score multiplier to the same effect, meaning these are not universal solutions. As a result, rewards cannot directly target gameplay elements for risk of harming rehabilitation.

Score multipliers result in less playtime for participants that use them optimally, and no change to those that do not. Implemented gamification elements must not incentivise altering the speed or lowering the amount of time a participant spends playing Balance-Land. A challenge such as “Play Y Environment for Z minutes” fits this criterion but runs the risk of forcing a participant to overstimulate, again working counter to the rehabilitative potential of Balance-Land.

7.5.2 Webcam-based Eye Tracking

The largest cause for concern about the development of features in Balance-Land has been the use of coping strategies. Any data gathered on symptom evocation may always be lower than intended due to the potential for participants utilising a coping strategy. This makes any decision about whether a feature should be altered due to lack of symptom evocation difficult, as the feature may actually be working entirely as intended, but have participants exhibit these coping strategies and receive feedback the feature was not performing as intended. This was one of the reasons why many changes to Balance-Land tended to focus on adding new features rather than removing them.

The best way to investigate this would be with eye tracking. Recent developments in technology have allowed webcams to be set up and easily usable as eye trackers (Wisiecka et al., 2022; Yang & Krajbich, 2021). Integrating webcam-based eye tracking with Balance-Land would allow for a more robust assessment of features, as it could be determined whether they were being used in the intended manner. However, this does raise ethical concerns over participant privacy and introduce a privacy barrier. The youngest participant recruited throughout the development of Balance-Land was 14 (approved via Cardiff and Vale Health Board and the School of Psychology, ethics committee NHS ethics, REC 13/WA/0119), which makes complete webcam-based eye tracking non-viable and raises ethical barriers. Rather, small-scale dedicated testing would yield the best results.

7.5.3 Balance-Land with other forms of rehabilitation

Balance-Land has evidence of rehabilitative potential. This likely works through the primary mechanism of visual desensitisation and a secondary mechanism of anxiety reduction through allowing participants to better understand their symptom triggers and limits. Much prior research has highlighted the rehabilitative benefit of a multi-pronged approach when dealing with visually induced dizziness (Byun et al., 2021; Popkirov, Stone, et al., 2018; Trinidade, Cabreira, Kaski, et al., 2023). This means Balance-Land would most likely be more effective if used in combination with pharmacological interventions or other anxiety-based forms of rehabilitation, such as cognitive behavioural therapy (Herdman et al., 2022).

7.5.4 Notifications and prompting

The feasibility study in Chapter 4 showed Balance-Land would benefit from offering more options to keep participants engaged. Rather than looking at the medical gamification literature, there are possible solutions in the education gamification area. One of the most popular gamified teaching applications is Duolingo (2012), of which there has been evidence it was an effective language learning tool (Vesselinov & Grego, 2012). When asking individual users what they found effective, Wang (2023) found that there were a variety of mechanisms participants found effective: learning streaks to build habits; constant positive reinforcement; and notifications to prompt participants to learn. What can be immediately noted is that two of those three mechanisms aim to build and maintain daily engagement. There were 10 participants that commented that they had difficulty fitting Balance-Land into their daily schedule or sticking to the recommended schedule *“5-10 minutes was a short amount of time to dedicate out of my day, which made it easy to integrate into my routine. However, it was easy to forget to play the game, especially if my daily routine changed.”* This evidence makes the idea of notifications and habit formation as a good idea, but there may be a negative: the second linear mixed model in Chapter 5 found prior symptom duration as a significant factor, with a possible explanation being participants forming habitual play patterns and being resistant to change. Leaving this as an optional feature could alleviate this issue, allowing for all the benefits without the downsides.

7.5.5 Mobile Phone as a Modality

One feature that was requested was a mobile phone version of Balance-Land. This makes sense, as 97% of adults in the United States of America have a mobile phone (Center, 2024). This would make Balance-Land more accessible, from a hardware perspective. The current gameplay in Balance-Land is entirely left-click or drag and drop, which is compatible with touch-screen gameplay, meaning a mobile app version of Balance-Land is currently possible from a technical standpoint. The primary issue is the field of view offered by a mobile phone, which is much smaller than laptop or computer screens. Prior research has established full field visual desensitisation is effective at symptom reduction (Law et al., 2024; Pavlou et al., 2013), along with full field virtual reality headsets (Mandour et al., 2021; Xie et al., 2021). It is likely that reducing the field of view to that of a mobile phone would negatively affect the rehabilitative efficacy of Balance-Land, with one participant comment from Chapter 2 to support this. It is unclear whether increasing the intensity of the visuals of Balance-Land to compensate for the reduced field of view would be sufficient. However, the benefits of the mobile phone for accessibility and notifications for prompting users to complete their rehabilitation could outweigh the potential for reduced rehabilitative efficacy.

7.6 Summary

Balance-Land was iteratively developed from the ideas of participants, clinicians, and the recommendations from academic literature with the purpose of finding the minimum path to viability of a new form of vestibular desensitisation rehabilitation. Since the first pilot in Chapter 2, Balance-Land has changed from a procedurally generated series of islands into a world for participants to explore. Evidence from the thesis shows playing Balance-Land is associated with a reduction in VVAS symptoms, HADS anxiety scores, and HADS depression scores, with the first linear mixed model from Chapter 5 providing evidence of visual desensitisation over time, which means Balance-Land can be used for visual desensitisation rehabilitation. Chapter 6 implemented final recommendations from participants and were evaluated by clinicians, with the end result being a tool that can be used to rehabilitate visually induced dizziness, motivates participants, and is widely accessible.

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9 Appendices

9.1 Appendix 1

9.1.1 Visual Vertigo Analogue Scale

Hôpital juif de réadaptation
Jewish Rehabilitation Hospital

Visual Vertigo Analogue Scale

(Adapted from Longridge et al., 2002)

Indicate the amount of dizziness you experience in the following situations by marking off the scales below.

0 represents no dizziness and 10 represents the most dizziness

Walking through a supermarket aisle

0 ———————————————— 10

Being a passenger in a car

0 ———————————————— 10

Being under fluorescent lights

0 ———————————————— 10

Watching traffic at a busy intersection

0 ———————————————— 10

Walking through a shopping mall

0 ———————————————— 10

Going down an escalator

0 ———————————————— 10

Watching a movie at the movie theatre

0 ———————————————— 10

Walking over a patterned floor

0 ———————————————— 10

Watching action television

0 ———————————————— 10

from: J. Vestib Res. 2011;21(3):153-9.

9.2 Appendix 2

These first questions are general questions about using the game in the future and the RCT.

1. The game targets two main symptoms associated with PPPD: dizziness and anxiety. Would you prioritise reducing one of these over the other and why?
2. How do you think we should measure a reduction in PPPD symptoms?
3. What evidence would you want to see before you would be willing to recommend the game to a patient?
4. If these prior criterions were met, at what stage of diagnosis/rehabilitation would you recommend the game to patients?
5. Are there any reasons why you wouldn't recommend the game to patients with PPPD, assuming it was effective at reducing symptoms?
6. Would you be willing to inform your patients or other clinicians about our research, so they could take part in the RCT if they wanted to?
7. How long did you play the game for?

These next questions are more specific questions about how to improve different aspects of the game

Many of the patients who we think could benefit from the rehabilitation game will not be used to playing video games. We have tried to make the game as accessible as possible to people who might not be very used to playing games on a computer. But please keep this in mind as you play through the game.

1. Do you think the features of the game were sufficient? Is there a feature you would like to see added or removed? Would this impact whether you would want to recommend the game?
2. Do you think there should be any changes to the controls to make the game more accessible to patients?
3. We want to allow participants to have an option to look more freely in the game, such as viewing the top or bottom shelves in the supermarket, or the top of a tree. However, we were concerned this could make the controls too complicated. How beneficial do you think this feature would be for patients?
4. In the future we want to add in more virtual environments that reflect everyday situations that participants find themselves in. Are there any virtual environments that you think would benefit your patients?
5. Do you think the current gameplay modes (e.g. scrabble, hangman etc) are sufficient? Do you have any comments about how to improve them?
6. Do you think participants should pick and choose the visual difficulty (i.e. how complex and cluttered the environments are), or should clinicians be involved in the decision?
7. Some participants from earlier stages indicated they would play the game as much as they could if there was evidence the game was effective at

rehabilitation. Should limits be placed on the maximum frequency and duration a participant can play?

8. We have discussed the idea of asking participants to play the game when standing or walking (e.g. on a treadmill) for increased difficulty, similar to how physical vestibular rehabilitation progresses. How do you think this would impact rehabilitation effectiveness? Are there any drawbacks to playing the game while standing or walking?
9. Is there anything else you would change, add, or remove about the game?
10. The best way to teach participants to play the game has not been discovered. Two pieces of feedback from participants were either a short instruction video, a guide explaining buttons, or some pop-ups in-game explaining things. Do you think any of these would be sufficient for your patients, or would you prefer an alternative?
11. One of the planned additions to the game is other moving objects. For the Supermarket, this could be other customers. For a potential “Street” level, this could be moving cars. Does this sound like a good feature? Is there anything to keep in mind when implementing this?

9.3 Appendix 3

9.3.1 Table S1

Balance-related diagnoses reported by participants that completed time 2 (and in brackets for participants at time 1). (*) indicates PPPD diagnoses included prior diagnosis labels, e.g. visual vertigo. We asked participants to tick all that applied for a list of conditions, or to supply other 'balance-related' diagnoses. Participants were recruited globally online from the following countries: USA (60), UK (51), Canada (12), Australia (2), Norway (2), Italy (2), Brazil (1), Finland (1), Germany (1), India (1), New Zealand (1), and South Africa (1). At Time 2, this was reduced to: USA (25), UK (29), Canada (6), Australia (1), Norway (2), Italy (1), Finland (1), and South Africa (1).

Diagnosis	Control (n=39) (t1 n = 70)	Intervention (n=37) (t1 n = 68)	Recommended Playtime (n=17)	Low Playtime (n=20)
PPPD*	16 (29)	21 (37)	7	14
Vestibular Migraine	17 (35)	14 (26)	6	8
Meniere's Disease	7 (11)	3 (7)	1	2
Vestibular Neuronitis	3 (5)	5 (6)	4	1
BPPV	2 (4)	5 (9)	4	1
Bilateral Vestibular Loss	4 (7)	0 (4)	0	0
Labyrinthitis	1 (2)	0 (1)	0	0
Vertigo from head trauma	3 (5)	1 (2)	0	1
Dizziness or vertigo due to stroke	1 (2)	0 (0)	0	0
Vestibular Schwannoma	0 (1)	1 (2)	1	0
Mal de Debarqument (MDDS)	0 (1)	0 (2)	0	0
Other	7 (15)	2 (9)	0	2
	1. Anxiety 2. Cervical vertigo 3. Endolymphatic hydrops 4. Vestibular tone imbalance, Peripheral Vestibular Disfunction 5. Binocular vision dysfunction, cervical spine dysfunction 6. Covid 7. Vestibular dysfunction	1. Autoimmune inner ear disease 2. Nerve damage due to lyme		1. Autoimmune inner ear disease 2. Nerve damage due to lyme

9.3.2 Table S2

Measured characteristics at screening stage for participants invited to enrol (meeting criteria for VVAS score and age) who joined or did not join the study.

	Participants who enrolled N = 138	Participants who declined N = 233
VVAS Severity	70.8	65.4
Age (years)	51.5	54.1
Gender % (female; male; other)	84;15;1	88; 11; 1
%PPPD	48	8
% Vestibular migraine	44	44
% Meniere’s Disease	13	21
% Vestibular Neuronitis	8	16
% BPPV	9	15

9.3.3 Table S3

Comparison between current study participants with PPPD, Vestibular Migraine and Meniere's Disease and published cohorts (selected for large N where available; other published cohorts tend to fall within the SD ranges below when N is sufficient).

	Study cohort at T1			Literature		
	PPPD	Vestibluar migraine	Meniere's Disease	PPPD[1]	Vestibluar migraine	Meniere's Disease
Age	50 ± 16	51 ± 13	51 ± 17	50 ± 14[1]	46 ± 15[3]	55 ± 14[5]
% female	81%	84%	81%	61%[1]	82%[3]	65%[5]
DHI	68.7 ± 14.3	72.0 ± 13.6	69.0 ± 13.5	~30-70[2]	36 ± 0.9[3]	23 ± 0.8[3]
HADS anxiety	11.1 ± 3.8	11.0 ± 3.9	9.4 ± 3.1	7.8 ± 4.2[1]	7.1 ± 3.3[4]	6.2 ± 4.4[7]
HADS depression	8.4 ± 3.8	8.8 ± 3.2	7.0 ± 4.0	6.5 ± 4.1[1]	6.0 ± 3.3[4]	4.1 ± 3.3[7]

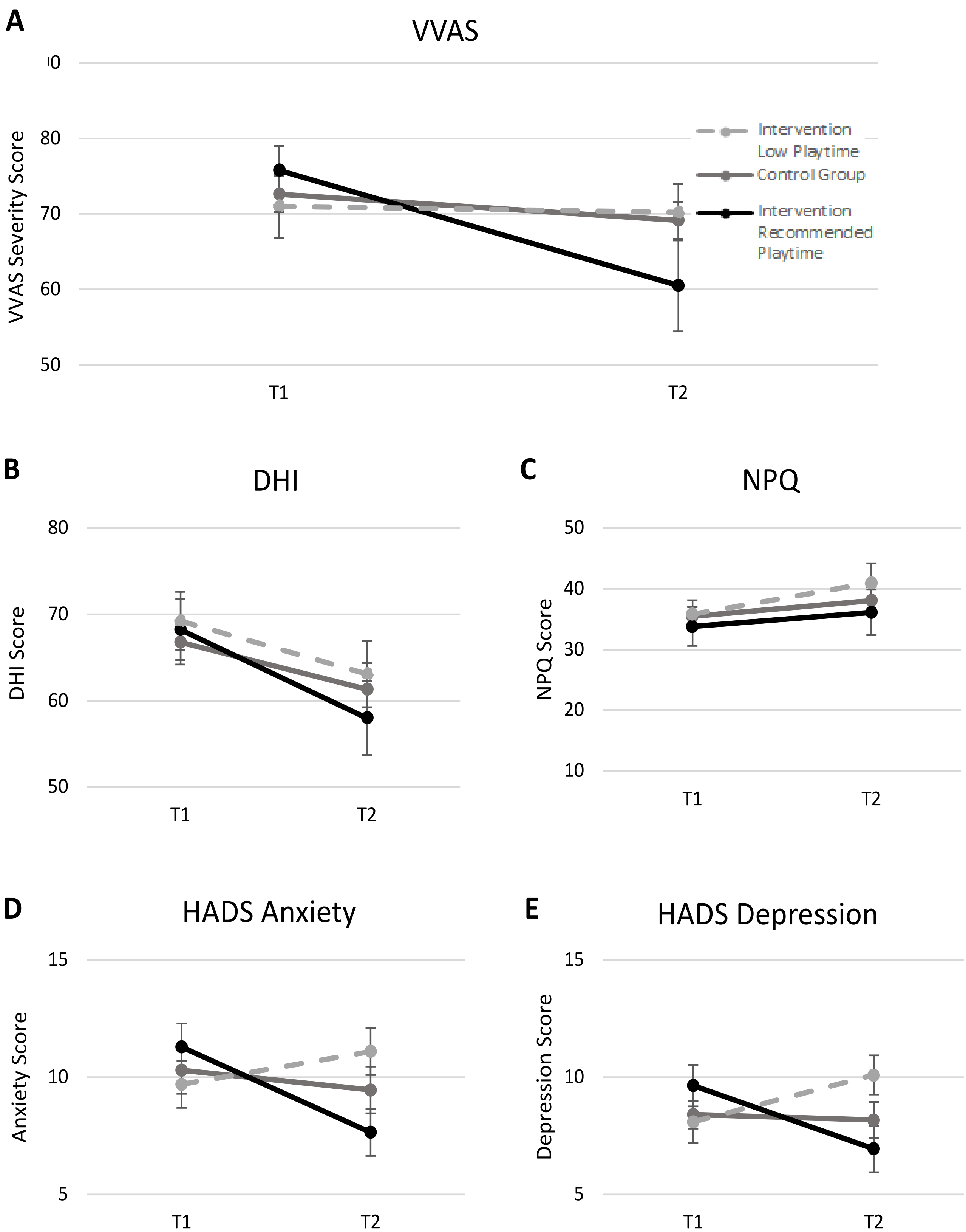
1. N=305 patients with PPPD reported by Axer, Finn, Wassermann, Guntinas-Lichius, Klingner, and Witte. 'Multimodal Treatment of Persistent Postural–Perceptual Dizziness'. *Brain and Behavior* 10, no. 12 (December 2020): e01864. https://doi.org/10.1002/brb3.1864.
2. Approximate DHI score range for N=122 patients taken from Figure 4 in Zhang, Jiang, Tang, Liu, and Li. 'Older Patients with Persistent Postural-Perceptual Dizziness Exhibit Fewer Emotional Disorders and Lower Vertigo Scores'. *Scientific Reports* 12, no. 1 (13 July 2022): 11908. https://doi.org/10.1038/s41598-022-15987-w.
3. N=365 from Chari., Liu, Chung, and Rauch. 'Subjective Cognitive Symptoms and Dizziness Handicap Inventory (DHI) Performance in Patients With Vestibular Migraine

and Menière's Disease'. *Otology & Neurotology* 42, no. 6 (July 2021): 883–89. https://doi.org/10.1097/MAO.0000000000003081.

4. N=74; Kim, Lee, and Heo. 'Prevalence and Contributing Factors of Anxiety and Depression in Patients with Vestibular Migraine'. *Ear, Nose & Throat Journal* 103, no. 5 (May 2024): 305–12. https://doi.org/10.1177/01455613231181219.
5. N=5508 MD cases; Bruderer, Saskia G., Daniel Bodmer, Nadja A. Stohler, Susan S. Jick, and Christoph R. Meier. 'Population-Based Study on the Epidemiology of Ménière's Disease'. *Audiology and Neurotology* 22, no. 2 (2017): 74–82. https://doi.org/10.1159/000475875.
6. N=122, Söderman, Bagger-Sjöbäck, Bergenius, and Langius. 'Factors Influencing Quality of Life in Patients with Ménière's Disease, Identified by a Multidimensional Approach:' *Otology & Neurotology* 23, no. 6 (November 2002): 941–48. https://doi.org/10.1097/00129492-200211000-00022.
7. In a larger study of N=358 MD volunteers (Kirby, Sarah E., and Lucy Yardley. 'Cognitions Associated with Anxiety in Ménière's Disease'. *Journal of Psychosomatic Research* 66, no. 2 (February 2009): 111–18. https://doi.org/10.1016/j.jpsychores.2008.05.027.) mean and SD HADS are not given, but mean anxiety score can be estimated to be over 8.7 given the information on proportions in each severity category.

9.3.4 Figure S1

Indications of rehabilitation effects for participants who adhered (N=17) or did not adhere (N=20) to recommended playtime. These groups did not differ in mean baseline VVAS ($F(2,73)=0.44$), symptom duration ($F(2,73)=0.12$), and age ($F(2,67)=1.16$), or counts of reported diagnoses (see Table 1 in main text and S1 above). Plots are a simplification of the data provided in the correlation plots in Figure 4 of main text. VVAS scores reduced for participants that played for the recommended time, while no reduction was evident for participants who played less, or for the control group (two-way 2 (Time 1 and Time 2) x 3 (Control, Recommended playtime Intervention, Low playtime Intervention) mixed ANOVA with repeated measures, interaction $F(2,73) = 4.33$, p = 0.017). DHI and NPQ showed no group x time interaction ($F(2,73) = 1.2$; $F(2,69) = 0.2$). Both anxiety and depression scores decreased for the group that played the recommended amount of time, while no reduction was evident for participants who played less or for the control group ($F(2,70) = 3.5$, $p = 0.037$, $F(2,70) = 3.5$, $p = 0.036$). Error bars are SEM. Shaded areas indicate categories associated with each measure, where available (for VVAS and DHI, pink=severe, orange=moderate; for HADS, pink = clinically diagnosable, orange = borderline, green = normal).


A
VVAS
VVAS Severity Score
80
70
60
50
T1
T2
Intervention Low Playtime
Control Group
Intervention Recommended Playtime
B
DHI
DHI Score
80
70
60
50
T1
T2
C
NPQ
NPQ Score
50
40
30
20
10
T1
T2
D
HADS Anxiety
Anxiety Score
15
10
5
T1
T2
E
HADS Depression
Depression Score
15
10
5
T1
T2

9.4 Appendix 4

9.4.1 Exit Interview Questions

1) What did you enjoy about the game, if anything?
2) What are your thoughts on the different word games you can play in the game? What games would you prefer in the future?
3) What did you think about the range of virtual environments to choose from (e.g. dessert, forest, supermarket)? Are there any more you would like to see in the future?
4) What would motivate you to play the game more?
5) What sort of feedback do you like to see about your rehabilitation progress in the game?
6) How did you find learning how to play the game?
7) How difficult was it?
8) How long did it take you to figure out the controls of the game?
9) Are you confident you know what each button does?
10) Was there anything in the game that was confusing or did not work in the way you wanted it to?
11) How much control did you feel like you had over how your symptoms were triggered? Did you slow down and speed up or go to different environments depending on your symptoms?
12) Throughout the course of the study, did you change the way you interacted with the game based on your symptoms?
13) How did you decide what environment to play in each day (the desert, the woodland or the supermarket?
14) Since the start of the study, do you think your symptoms have changed in real world environments? Is this due to the game or something else?
15) Some people report having anxious thoughts about their dizziness. Do you have these? Have your thoughts around anxiety changed throughout the study? Why do you think this is?