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Design and Evaluation of a Virtual Reality Game to Improve Physical and Cognitive Acuity

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Completed Research

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Abstract

Physical and mental health are both integral to healthy living and ageing, and a causal-cum-symbiotic relationship has been observed between the two. Physical and cognitive activities such as exercise and board games are known to promote healthy ageing. In this regard, highly engaging lightboard games are known to improve hand-eye coordination, reflexes, and motor skills for individuals. Immersivity of virtual reality games can transform mundane and repetitive exercise routines into stimulating experiences, and they can be utilized by users to improve physical and cognitive performance from the comfort of their homes. In this study, we adopt design science framework to design, develop and evaluate a VR BATAK lightboard game to improve physical reaction, hand-eye coordination, visual memory and cognitive processing. Based on the findings from evaluation over three phases, we propose three design principles related to accessibility, sensory cueing and cognitive loading, as theoretical and practical contributions of this study.

Keywords: virtual reality, physical performance, cognitive acuity, design science research

Introduction

The COVID-19 pandemic has caused disruptive changes in our lifestyle resulting in declining physical and cognitive fitness among the aging population (Makizako et al. 2021; Amini et al. 2021). Social isolation during the pandemic period induced a decline in physical and cognitive activity among older adults (Noguchi et al. 2021). Physical and cognitive acuity are two important components of overall health and well-being in individuals, and specifically for older adults (Taylor 2013). Physical acuity relates to the level of physical ability and fitness of a person based on strength, endurance, balance and coordination. Cognitive acuity is the mental ability of a person with respect to memory, attention and creativity. Physical and mental health are both integral to healthy living and ageing, and a causal-cum-symbiotic relationship has been observed between the two (Ohrnberger et al. 2016). Regular physical activities decrease the risk of chronic diseases such as heart disease, stroke, and diabetes (Lee et al. 2012), and enhance cognitive functions (Colcombe and Kramer 2003). Motor skills are critical for performing everyday physical activities such as walking, running, *etc*., for individuals. Memory also represents a key cognitive skill that we employ on a daily basis for guiding our physical activities and recalling and planning events. Brain regions responsible for motor functions and memory are highly vulnerable to age-related effects, and these skills can be severely impaired by disorders such as dementia, depression and stroke. Cognitive training can improve memory and other cognitive functions in older adults (Belleville et al. 2011).

Recently, immersive technologies like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are gaining popularity as a tool for improving human health in various ways such as physical and cognitive training especially in pain management (Li et al. 2011), mental health (Freeman et al. 2017), and physical rehabilitation (Laver et al. 2017). VR, AR and MR are all related technologies that involve creating immersive experiences, but they differ in the degree of immersion and interaction they provide (John et al. 2022). VR is a fully immersive experience that transports users to a virtual environment, while AR overlays digital information onto the real world, and MR combines virtual and physical elements to create an immersive mixed reality environment. VR is defined as a computer-generated simulation or environment that can be experienced through VR devices such as Meta Quest (Bernard et al. 2018). VR environments enable perceived presence and full immersion as the users see the virtual world in their head set with a seamless overlay of 2D and 3D objects such as audio files, videos and textual content. It helps to recreate a pleasing environment at your desired location where you can walk around and engage in the virtual world (John and Wickramasinghe 2020). Studies have shown that VR has several advantages for older adults. For example, Rose et al. (2019) found that a VR-based cognitive training program improved attention and processing speed in older adults. VR-based rehabilitation programs have been shown to improve balance, gait, and mobility in older adults, leading to a reduction in falls and improved quality of life (Laver et al. 2017). Shen et al. (2022) found that VR-based social cognition and interaction training for patients with Schizophrenia (a disorder that affects a person's ability to think, feel and behave clearly) experienced improved emotion and meta cognition. Thus, considering the advantages of VR environment to engage older adults and to improve their physical and cognitive acuity, this study proposes a VR game to this end.

Physical and cognitive activities such as exercise and board games (Altschul and Deary 2020) are known to promote healthy ageing, and are regularly featured in intervention activities at residential aged-care homes (Parekh et al. 2018). To add on, according to World Health Organization (WHO), by 2030, 1 in 6 people in the world will be aged 60 years or over (Ageing and Health 2022). According to the Australian Institute of Health and Welfare, by 2030, 17.8% of the Australian population will be aged 65 and over (AIHW 2023). Global action plan on physical activity 2018-2030 propose various action plans and it clearly states in action 3.2 that *"…research and development agencies and technology companies should develop and test cost effective approaches using mobile and wearable devices to promote physical activity…"* (WHO 2019). Despite significant investments towards aged-care reforms (Aged Care Budget 2023), very few studies have explored the value of immersive health interventions (e.g., Virtual Reality applications) for improving physical activities and cognitive activities for the ageing population (Thach et al. 2023). In his regard, the highly engaging BATAK lightboard game (Wood 2010), known to improve hand-eye coordination, reflexes, motor skills, and stamina for individuals, holds promise as a stimulating physical activity. Recently, video and VR games (D'Cunha et al. 2019; 2021) have also been found to be effective in engaging users and improving dementia and stroke-related outcomes. The immersivity of VR games can transform mundane and repetitive exercise routines into competitive and stimulating experiences, and they can be utilized by users to improve physical and cognitive acuity from the comfort of their homes. Hence, the aim of this study is to design, develop and evaluate a VR game to improve physical and cognitive acuity of users.

In what follows, we review literature on VR and the studies that focused on the use of VR to improve physical and cognitive acuity of users for health and medical reasons. We then develop the theoretical foundations of the study by drawing on design science research. The empirical setting of the study is then presented, and the methodology adopted explained. Finally, a three-phase user evaluation of the application and related findings are presented.

Literature Review

In this section we review earlier work on VR and literature that uses VR for improving physical and cognitive acuity of users.

VR was first introduced as a training tool for airline and air force pilots during the 1990s (Thomas & David 1992). VR is a technology that creates a fully immersive, computer-generated environment that completely replaces the user's physical surroundings (Gasques, et al. 2021). Users typically wear a VR headset that covers their eyes and ears, and often use handheld controllers to interact with the virtual environment. VR is commonly used for gaming, training simulations, and entertainment. Meta Quest is an example of example of a VR device and Beat Saber is a VR game. AR is a technology that overlays computer-generated content onto the real world, enhancing the user's perception of reality (John et al. 2022). AR typically involves using a smartphone or tablet camera to capture the real-world environment, which is then augmented with computer-generated graphics or information. AR can be used for a variety of applications, such as marketing, education, and entertainment. Niantic Labs' Pokémon Go is an example of an AR application in a mobile phone. MR is an advanced version of VR and AR, allowing users to interact with virtual objects termed as holograms that are anchored to the real world (Stretton et al. 2018). MR typically involves using a headset that combines cameras, sensors, and displays to create a seamless blend of the real and virtual worlds. Microsoft HoloLens is an example of MR device and HoloPatient is an example of mixed reality application. The choice between VR, AR and MR depends on the specific purpose of use. VR is much more affordable than MR with respect to cost and accessibility but will isolate users from the physical world. This study uses VR environment due to the affordability and accessibility to design and test the initial phase of the application.

VR facilitates seamless interaction with the digital world and is used in health, education and business. Martin et al. (2020) demonstrated the deployment of the VR device helped to support the delivery of remote care in COVID-19 hospital environments with reduced exposure to COVID-19 infections (Martin et al. 2020). An interactive and immersive surgical mentoring by experts from a remote location helped novice surgeons perform surgical procedures during an emergency (Gasques, et al. 2021). Although VR demonstrates immense capacity for education, health and business, adoption of the technology has barriers including the cost of the device, technical limitations and the user's proficiency (Gasques, et al. 2021). The affordances of virtual reality have been well explored in the literature on the educational use of video games, although the immersive nature of more advanced VR technologies does appear to enhance these effects (Clark et al. 2016).

The use of VR in sports has been widely studied in the context of its benefits for athletes, coaches, and professionals in the field (Neumann et al. 2018). Some of the characteristics of VR that were significant in sports such as cycling, running, and rowing were the presence of others in the virtual environment, competitiveness, autonomy, immersion, and the ability to receive feedback. In cycling, the introduction of avatars increased the intensity of cycling for older adults (Anderson-Hanley et al. 2011) and this was also found to be true in the case of competitive athletes (Synder et al. 2012). In a study conducted with athletes in weightlifting, VR was found to increase athletes weightlifting performance (Chen et al. 2015). VR technology was also found to be effective on training athletes with a race strategy that could improve energy management and performance outcomes. The degree of immersion in VR technology increased athletes' motivation and average speed. On the other hand, in comparison with an actual trainer, the avatar in VR environment reduced the perceived pressure to athletes during the training sessions (Ijsselsteijn et al. 2004). VR environment was found to increase the performance of athletes participating in rowing competitions (Murray et al. 2016) and reduce tiredness for athletes participating in cycling competitions (Plante et al. 2003). The augmented feedback provided in the VR environment helped athletes participating in rowing competitions to improve their performance compared to those who were not receiving regular feedback (Sigrist et al. 2015). Hence, studies related to the use of VR in sports clearly demonstrate that the degree of immersion results in improving physical acuity of athletes in a VR environment.

Statistics indicate that anxiety-related disorders are one of the significant mental disorders prevailing in communities (Carl et al. 2019). WHO report 301 million people were living with an anxiety disorder including 58 million children and adolescents in 2019 and the pandemic significantly increased such disorders by 28% (WHO 2022). It was also found that substantial treatment gap exists for anxiety-related disorders when an in vivo exposure was conducted using a VR environment (Carl et al 2019). Other benefits are cost effectiveness (Miloff et al. 2016) and user appeal (Powers and Emmelkamp 2008) when compared with traditional psychotherapy. VR environment was found to be effective for social anxiety disorder (Bouchard et al. 2017), posttraumatic stress disorder (Reger et al. 2016), generalized anxiety disorder (Repetto et al. 2013), panic disorder with agoraphobia (Meyerbröker et al. 2013), music performance anxiety (Bissonnette et al. 2015), public speaking anxiety (Wallach et al. 2009), school phobia (Gutiérrez-Maldonado et al. 2009), fear of falling (Levy et al. 2016), dental phobia, and arachnophobia (Miloff et al. 2016). Another important use of VR was its use as an intervention tool to rehabilitate patients who had stroke, Parkinson's disease and those who were recovering from neurological disorders (Zhu et al. 2021). For acute and chronic patients, VR has been successfully used for the treatment of pain management (Li et al. 2011). Some of the medical procedures where VR was successfully used include wound care and chemotherapy where multimodal sensory distractions of VR reduced the pain experienced by patients (Morris et al. 2009). VR was used in awake craniotomy to map social cognition and to test gesture communication where the neuroscientist communicated with the patient during the surgery (Bernard et al. 2018). Overall, VR is a promising research area to explore, especially considering the ways it can help in capturing user's social cognition and improving their cognitive acuity.

The above studies have explained how VR was used in improving the physical and cognitive performance of users. Hence, designing a gaming system that can measure the reaction time, hand-eye coordination and dexterity among users and older adults, will have immense value in examining and improving the physical and cognitive performance of users. Hence, the aim of this study is to design, develop and evaluate a VR game to improve the physical and cognitive acuity of users.

Methodology

The design, development, and evaluation of the VR game to improve physical and cognitive acuity follows the Design Science Research (DSR) method. DSR is an innovative approach that aims to address complex problems by creating practical and effective solutions through the integration of scientific knowledge and design principles. This research approach is highly important as a means of accumulating knowledge and acting on it, using a complex artifact in a real-world scenario. Hevner et al. (2004) defines DSR as a research paradigm that aims to create and evaluate new artifacts, such as models, methods, or systems, with the goal of solving real-world problems. The authors argue that DSR is distinct from other research approaches because it combines scientific inquiry with design principles to create practical solutions. DSR involves the creation of an artifact to improve the current state of practice and contributes to the existing research knowledge as a form of design theory. DSR is a widely used methodology in design of new artifacts in IS literature (John et al. 2016; 2022; 2023). The analysis of the artifact's use and/or performance, which leads to reflection and abstraction, is the core component of DSR. The relevance of the project is defined according to business needs. The rigor for the project is from an academic knowledge base and will be addressed through the research project. A cycle of design, development and evaluation is the key concept of DSR. For this study, there were three iterations of design, development, and evaluation. The first phase of the project involved designing an initial prototype, testing the application, and collecting expert feedback in a focus group discussion after demonstrating the application. The application was re-designed based on expert feedback. In the second phase of the project, users played both real game and VR game and compared the two. After re-designing the VR game based on the feedback from the comparative study, the third phase of user evaluation was by experienced general users about the overall usability of the game. This process of iterative design, development and evaluation followed DSR guidelines as illustrated in Figure 1 and detailed in Table 1. Thus, this study follows DSR evaluation recommended by Venable et al., (2012) by evaluating an instantiation of a purposeful designed artefact – the Virtual Human Benchmark (VHB) VR Game. This study attempts to establish its utility in terms of efficacy, efficiency, and satisfaction for improving the physical and cognitive acuity of users. The initial design and development steps are presented below while the iterative evaluation and findings are presented in the next section. Table 1 gives detailed explanation of how the DSR guidelines were applied.

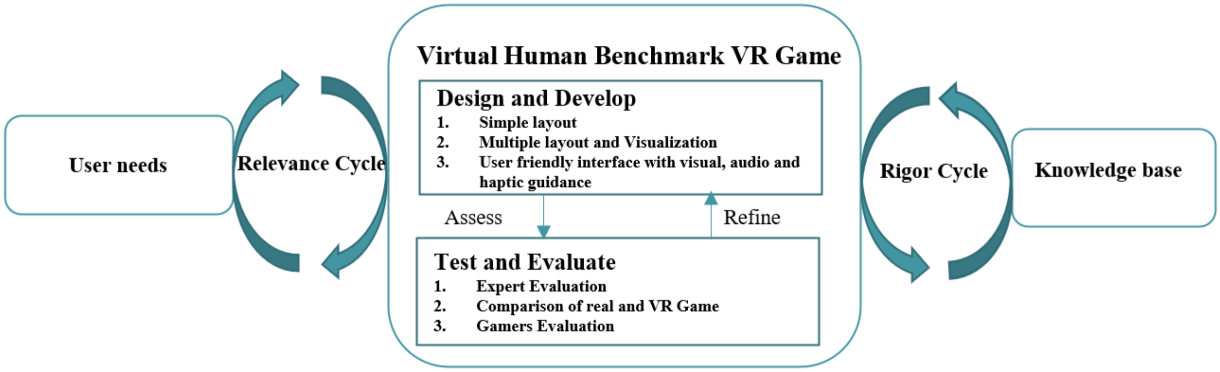

Figure 1. Applying DSR in designing and evaluating a VR Game

Design Science Research Guidelines	Virtual Human Benchmark
Design as an Artefact	Virtual Human Benchmark was developed as a gamified virtual reality application to improve physical and cognitive acuity.
Problem Relevance	To build an innovative approach to address the need for improving physical and cognitive abilities particularly in older adults from the comfort of their home. To provide appropriate design principles towards developing VR based games for general users and particularly for older adults.
Design Evaluation	One phase of testing by research team and developers was followed by three phases of evaluation by various users. Thus, it resulted in an iterative process of design and evaluation. Users tested the VR application with a physical system to compare their experience. Health experts, VR designers, general users and gamers tested the VR application to evaluate their satisfaction and if the solution was fit for purpose.
Research Contributions	First contribution is that the VHB game was developed and tested to help improve the physical and cognitive acuity of users. Second contribution is that the DSR methodology adopted in iterative design, development and evaluation of the application resulted in three design principles to effectively develop a VR based gamified application.
Research Rigor	Theoretical foundations and conceptual models drawn from information systems, human computer interaction, VR application development guidelines and protocols, and ethics guidelines were used to inform the development cycles and evaluation process.
Design as a Search Process	The design of a virtual BATAK system was the result of a search process that led to an innovative idea. Monitoring and evaluating physical and cognitive abilities were the result of the design process and complete risk mitigation was essential in the design of VHB game.
Communication of Research	VHB was presented to a series of experts in health and information technology areas. It will be presented in an international conference to collect feedback to refine the research towards extending the application for aged adults, rehabilitation, and dementia community.

Table 1. DSR guidelines to design and evaluate the Virtual Human Benchmark

Design of the VR Game: The design of the VR Game was based on intensive review of existing games used to improve physical and cognitive activities by the research team and students who were involved in the design and development of the game. A highly engaging BATAK lightboard game (Wood 2010) to test the reaction time, hand eye coordination was identified by the team. Thus, the Virtual Human Benchmark (VHB) VR game was designed to stimulate the BATAK reaction test in a 3D immersive space to test and improve reaction time and hand-eye coordination. It typically consists of a large board with a series of illuminated buttons that light up in a random pattern, and the player must quickly press the buttons as they appear. The BATAK Reaction Test has been used in various settings, including sports training, rehabilitation, and cognitive testing. Katsikas et al. (2018) investigated the effectiveness of the Batak reaction test in upper limb rehabilitation for stroke patients and found that the use of the BATAK reaction test significantly improved upper limb function and coordination in stroke patients. Hadlow et al. (2019) evaluated the effectiveness of BATAK reaction training on elite hockey players and found that the hockey players who trained with the BATAK board showed significant improvements in their reaction time and hand-eye coordination compared to a control group. However, none of the studies were in a BATAK based VR Game Board. Hence, the design of the VHB game followed the design of a BATAK reaction test light board. Figure 2 and Figure 3 illustrate a BATAK board and the VHB VR game board.

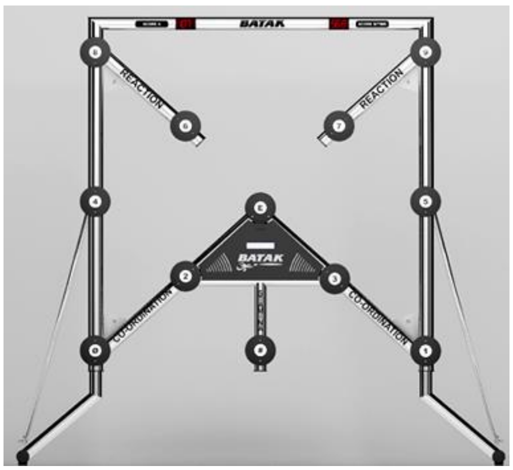

Figure 2. BATAK Reaction Test Light Board

Figure 3. Virtual Human Benchmark VR Game Interface

The design of VHB game consist of three modes: the reaction, accumulator, and sequence game modes:

- **Reaction mode:** The reaction mode captures the speed of the player reaction by recording the time taken to click the controller button after the light is switched on the BATAK board. Reaction mode is used to measure a player's reaction time (RT). RT is an important measure which is measured as the response to a stimulus. Reaction time can be influenced based on age, sex, left or right hand, vision, practice, fatigue, breathing cycle, personality types, exercise, and intelligence of the individual (Jain et al. 2015). In reaction mode, the VHB lightboard will light all targets at random intervals, and the user reacts by pressing the controller button as fast as possible. This process repeats over a stipulated number of trials (typically 5 or 10), and the reaction time for each trial is recorded. This mode assesses the user's ability to process visual information and physical reflexes.
- **Accumulator mode:** The speed, hand trajectory, and accuracy are important measures to understand peripheral awareness, dexterity and hand-eye coordination of a player and these can be measured using accumulator mode. Replicating the real-world BATAK functionality, the VHB lightboard will light up a single target button at random intervals, following which the user needs to strike the lit target quickly for another target to light up. This mode seeks to motivate the user to strike as many targets as possible during a set time limit of 30/60 seconds, and challenges the user's motor agility, hand reach range and dexterity.
- **Sequence mode:** While the reaction and accumulator modes primarily assess physical acuity, the sequence mode seeks to examine visual memory and cognitive processing. In this mode, the VHB lightboard will flash a sequence of targets one after another, which the user must repeat. The sequence pattern complexity will increase over trials until the user makes an error or the game completion following maximum number of trials thereby testing their visual memory.

Development of VHB Game: Overall, the VHB VR game was developed to train and improve one's physical and cognitive acuity by monitoring the reaction time, hand-eye coordination and visual memory.

The requirements for different game modes were derived from the Human Benchmark web application[1] and the BATAK reaction test (Wood 2010). VHB was developed using the Unity game engine, and other software packages used include the JetBrains Rider integrated development environment, Meta software development kit (SDK), Universal Render Pipeline for rendering shadows and textures, and the Windows Mixed Reality SDK. The game has been successfully tested by the developers and the research team members on the Meta Rift, Quest 2 and HP Reverb G2 VR headsets, and the minimum hardware specifications for an optimal development and testing experience, and game launching onto PC include: Nvidia GTX 970/AMD R9 290 GPU, Intel i5-4590 equivalent CPU, 8GB RAM, HDMI 1.3 video output, 3x USB 3.0 ports and 1x USB 2.0 port for the base station to track controller movements, and Windows 7 SP1 64-bit OS.

To ensure that the VHB game seamlessly renders on multiple screens, a low-polygon design is adopted to design the scene model and assets (such as hands). To further enable the application to render at 75fps or higher frame rate so that the user feels immersed in a 3D environment, complementary colors like white, blue, and orange are utilized for scene guidance. Blue color is used to denote non-interactive assets, while interactable such as the game buttons or mode selection menu are colored orange. An initial screen to inform and obtain user consent for data collection, is followed by the game selection menu. Upon selecting the desired game mode, the user will move towards the BATAK lightboard at the center-stage and press the 'start' button to begin playing. A game manager module manages the game modes, controls how the BATAK lightboard buttons should behave in each mode, and how user data should be saved after a game. A lightboard manager is also implemented to provide granular control relating to button activation, track activated buttons, and record whether the user presses the correct targets (for the accumulator and sequence modes). In terms of the data logged for each user, apart from summary data in the form of the score achieved and time taken, snapshots relating to each trial are also recorded. A reaction snapshot includes reaction time and the time between successive lightboard flashes (random interval between 5–15s). The accumulator snapshot records details such as the button position, time between two button presses, and remaining time, while key entries within a sequence snapshot include the flashed sequence and sequence length, repeated sequence pattern, time taken to repeat pattern and time between target presses. The summary plus snapshot data per user are stored via json files.

To streamline analysis of collected datasets, a secondary application termed "VHB Insights" is developed to provide a simple drag and drop interface to produce graph's, summaries, and tabular results for the new extensions to the datasets. VHB Insights allows all users to see their performance visually and was built using Electron, React and Typescript. The details are available in the VHB Insights webpage[2]. Figure 4 illustrates how the user performance data are used to generate visualizations with VHB Insights. Feedback from health experts suggested that these analytics can provide actionable insights to allied stakeholders like therapists and clinicians utilizing VHB for training/rehabilitation purposes. The JSON accumulator log is the input to the VHB insights tool to generate visualizations. Figure 4 presents details like the user score, cumulative hand displacement (in meters), distribution of left/right hand usage as a pie-chart, button press sequence and a scatter plot showing remaining game time vs elapsed time between successive button presses (in seconds). The hand-tracking capability of the Meta device was used to output the distance between the user's hand and target button over time Figure 5. Hand tracking can be particularly useful for evaluating stroke rehabilitation outcomes, as stroke patients need repeated training to reach out for objects and grip them (Seidler et al. 2010; Dean and Shepard 1997).

The initial design, development and testing by the development and research team was conducted from February 2022 to June 2022. The following section details the three phases of evaluation, relevant findings and the design principles used to re-design the VHB game. A short video of the final VHB game is available in the link[3].

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[1] https://humanbenchmark.com/

[2] https://virtual-human-benchmark.web.app/

[3] https://www.youtube.com/watch?v=AdEO4dqhZBI

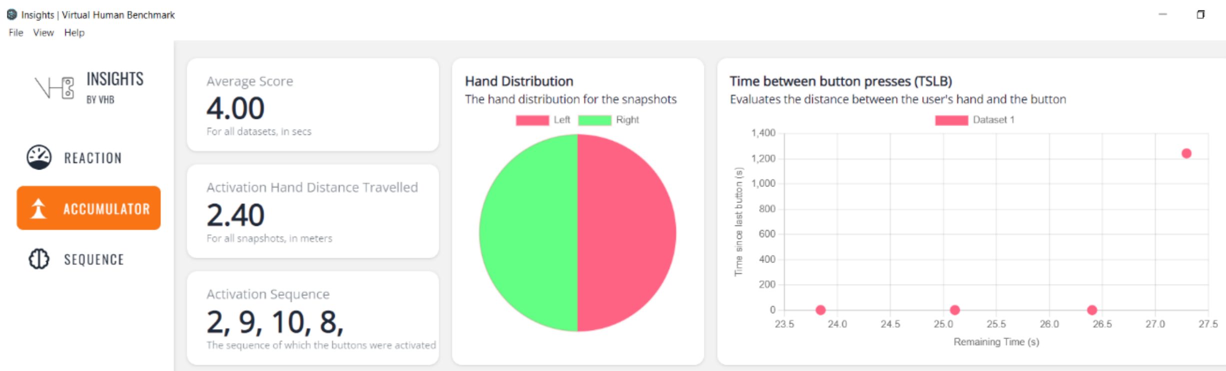

Figure 4 Visualization of the captured data with VHB Insights App

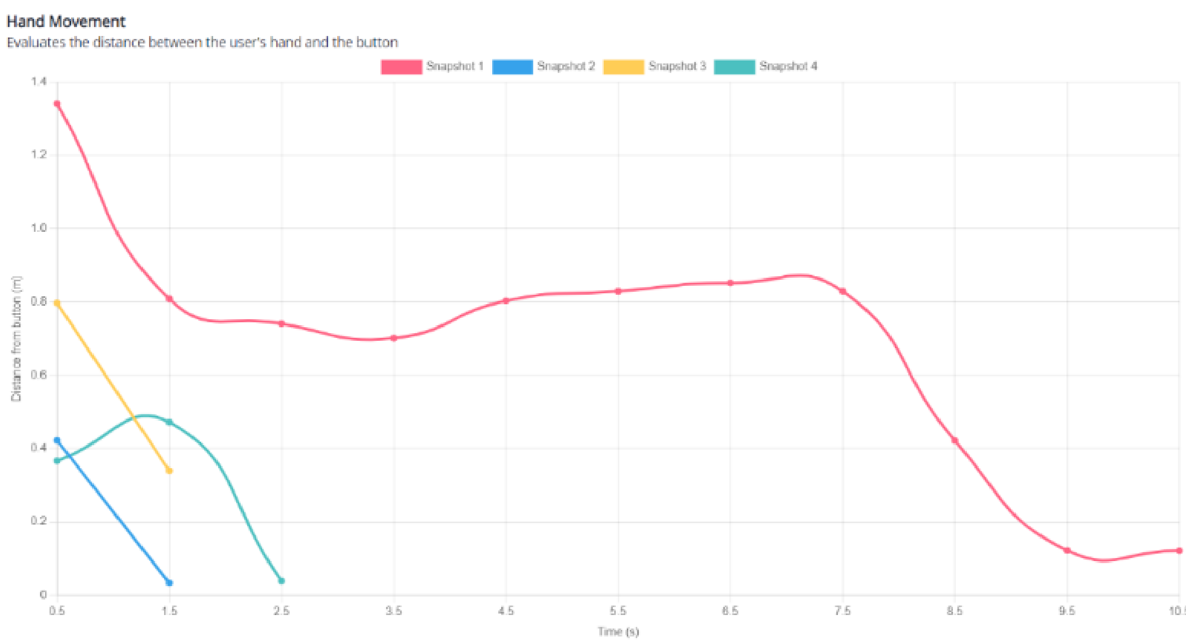

Figure 5. Visualization of the hand movements captured by the Meta Quest Hardware

Evaluation and Findings

The VHB VR Game prototype was evaluated in three phases and iteratively redesigned based on the feedback from the users. The first phase of evaluation was conducted in June 2022, the second phase of evaluation in October 2022 and the third phase in December 2022. Evaluation phase aimed at an instantiation of a designed artifact to establish its utility and efficacy for using the VHB game to effectively measure the physical and cognitive abilities of the player (Venable et al. 2012). Multiple evaluations, combining multiple evaluation strategies targeting multiple set of users were conducted in three phases as listed below.

Evaluation of VHB Game – Phase 1 Expert Feedback: An initial version of the VHB game was presented to a focus group consisting of seven industry and academic experts for their evaluation and feedback. These included a VR specialist, a neuro-rehabilitation specialist, two sports health experts, a bio-mechanist and two researchers developing VR applications for health and well-being. The study was conducted in the Human Centered Research Lab and the experts were able to view a live demonstration of the game and test the game. The focus group discussion lasted for approximately 45 minutes. Their feedback was collected in a written form and analyzed by identifying their key recommendations. Their feedback is summarized as follows:

1. Experts conveyed positive impressions and concurred that the VHB game could induce positive outcomes in the sports and health domains. Specifically, the VHB reaction and accumulator modes (and equivalently the BATAK lightboard game) can improve visual processing and visio-spatial skills which involves recognizing brightness/darkness and is crucial for sports training and hand-eye coordination (Millard et al. 2021). Additionally, the sequence mode can induce cognitive stimulation, which is known to benefit patients with mild-to-moderate dementia (Woods et al. 2012).
2. A number of experts preferred to have a game version that supports seated users, where the score was computed based on user ability and independent of time. One expert recommended a game mode where the user had to reach beyond 150% arm's length. These recommendations were aimed at addressing requirements of specific demographics such as stroke patients and training them to improve their sitting balance and object reaching abilities (Dean and Shepard 1997).
3. One expert also recommended the use of multiple lightboard layouts to support users with diverse requirements and abilities. All experts advocated the need for user experience surveys involving both gamers and non-gamers. In response to these recommendations, the game design was adopted to include multiple lightboard layouts as shown in Figure 6. The 3×3 grid and small circle layouts were designed to support users with limited reach, while the large circle, four corner and border layouts were intended to support users requiring training specific to upper limb strengthening and object reaching.

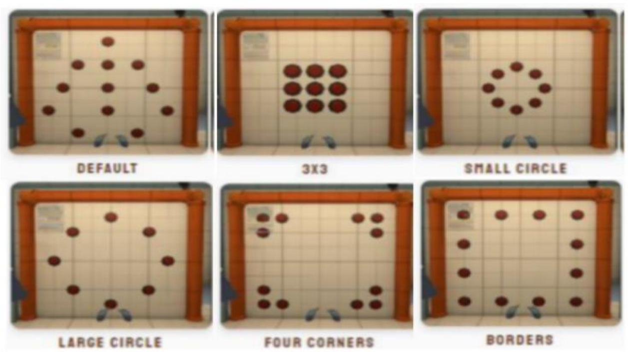

Figure 6. Designed multiple lightboard layouts

Evaluation of VHB Game – Phase 2 Real Game vs Virtual Game User Study: After redesigning and improving the VHB game based on expert feedback, a user study was conducted to compare user experience with the real-world BATAK and the VHB counterpart. To compare the VHB game experience against with the real-world BATAK lightboard, we performed a study with 20 healthy users at Questacon, Science Centre. Healthy users were users aged 18 and above without any disability. Experts who gave feedback were not involved in this phase. For a fair and exact comparison, users played the BATAK game and the VHB accumulator mode back-to-back and filled a questionnaire soon after to share their experience of the physical game and the VR game. The specific aims of this phase of evaluation of the artefact (Veneable et al. 2012) was to examine if (a) user performance was similar in the physical and virtual game versions (assuming similar levels of comfort with both), and (b) there were significant differences in user impressions with respect to game attributes such as engagement, ease of play, ease of light tracking, simplicity of button press/control (physically vs via the VR touch controller) and level of focus/distraction during the game play in the physical vs virtual environments (see Fig. 7).

Phase 2 user study setting was arranged at the Science Centre Questacon, so that users can access the real BATAK board. Eligible visitors, who were aged over 18 and without any physical disabilities, arriving at the BATAK board exhibit in Questacon were recruited for the study. Informed consent was obtained from these participants as per ethics approval, following which they were asked to additionally play the VHB accumulator game with the default lightboard layout using a Meta Quest headset. The BATAK and VHB lightboards identically comprised 12 targets. Figure 7 presents an exemplar user playing the BATAK and VHB games within the same physical environment. The order of playing the virtual and real games was counterbalanced across participants. Upon completing both the games, users had to complete three online questionnaires: two concerning the physical and virtual game versions, and a third comparing the two. Users needed to provide both quantitative and qualitative responses in the game-specific questionnaires. Quantitative responses mainly involved specifying scores on a 1–5 Likert scale for the attributes specified above, while qualitative responses denoted justifications for these scores. The comparison form involved selecting one of two alternate choices, plus explanations to support the selections. Including user preparation time, game play and questionnaire completion, each user took about 20 minutes to complete the study. 20 users (9 female, age range 31.2, 13 right-handed) took part in this study. 11 users reported that they frequently played video and VR games.

Figure 7. A user playing the BATAK game (left), and the VHB game via Meta Quest (right)

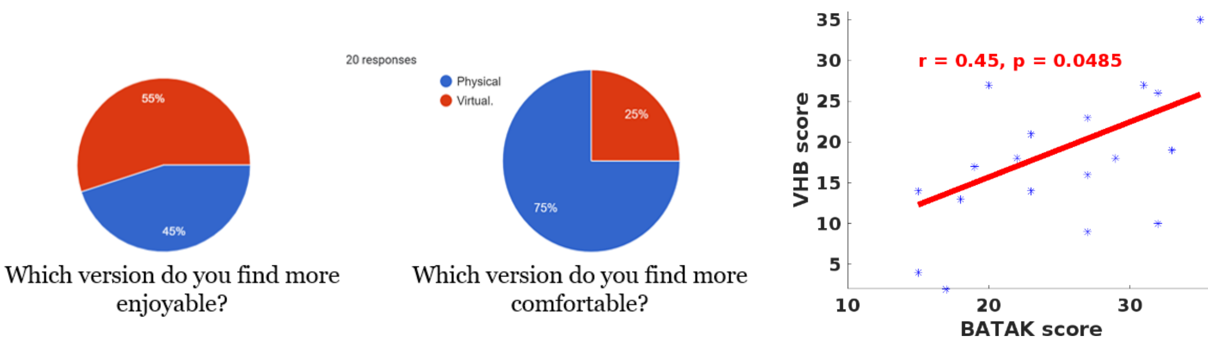

Figure 8. User preferences with respect to BATAK vs VHB Game

As illustrated in figure 8, the user study resulted in a moderate and statistically significant Pearson correlation between the user BATAK and VHB game scores, implying that the VHB game is ecologically valid, and agile users generally score well in both versions. Figure 9 presents a summary of the BATAK vs VHB game comparisons and conveys that while users generally enjoyed playing both versions, the physical BATAK was more comfortable to play. The pros and cons of the physical BATAK were further highlighted by qualitative comments, some of which are listed below:

- *It is easier than it looks, the field of view limits visibility of lit buttons in the corners of your vision.*
- *I'm only 152cms tall and the lights at the extremities were harder to reach and spot via peripheral vision.*
- *The BATAK lightboard was quite good, however, I found it difficult to see the peripheral buttons when they lit up.*

The above remarks confirm that while the BATAK game play was facile, there were limitations with respect to its physical design and tracking of lights, especially those at the corners. Comments on the VHB game included:

- *Highly engaging, I found myself immersed to a point where it felt realistic and enjoyable.*
- *I found it more difficult to hit the buttons. The game wasn't as fluid as I thought it would be.*
- *Interesting, difficult at first mostly with pressing the virtual buttons.*
- *The experience was good. The application was well built, and easy to use, the contrast of a lit button was higher which made identification easier. The triangular pattern made for a more efficient eye scanning pattern as opposed to the physical BATAK test.*

These impressions convey that (a) the VHB game design was perceived to be immersive and realistic, and (b) the lightboard structure plus the illumination contrast made light tracking much easier. However, button activation via the touch controller was difficult, and considerably contributed to user frustration and distraction. These observations were further reinforced along with other issues such as weight of the VR headset in some comparative remarks listed below:

- *I would rate the virtual version higher, as I found myself more immersed and had a higher quality experience.*
- *The physical board was more comfortable and easier to use.*
- *The virtual version was slightly less intuitive.*
- *Physical- No added weight on the head, the buttons were easier to press and more responsive.*

Overall, the user study revealed limitations of using VR devices and the design of the VHB game in particular. Discomfort with wearing the VR headset can be addressed via design of a more ergonomic VR device. Usability issues with the VHB game were mainly noted with respect to executing physical movements such as button control; it needs to be noted here that while the VHB game can be simultaneously projected onto a monitor during gameplay, the fact that the user study was conducted in an exhibit hall precluded this possibility. In the absence of any visual feedback, experimenters were only able to provide general guidance to users on executing game actions which was insufficient and resulted in user distraction and frustration.

To better guide users to execute physical movements through the game play, a second version of the VHB game (VHB v2) was developed with the following additional features:

1. ***Tooltips:*** *Tooltips including a text panel succinctly instructing users on how to perform physical actions (e.g., activate buttons or walk through the scene) were added to provide visual feedback (Figure 9).*

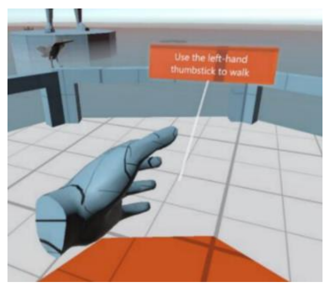

Figure 9. VHB v2 with additional features like tooltips

2. ***Radial View Displays:*** *Adaptive animations that were rendered according to perspective (head pose) were created to demonstrate the game mode to users.*
3. ***3D Audio:*** *3D spatial audio cues were incorporated to guide user attention to directions they are not facing. Examples include helper arrows with a pulsating sound communicating to the user to select/start a game mode, audio feedback of button clicks and auditory notifications signifying game starting and completion.*
4. ***Haptic Feedback:*** *In addition to 3D audio, haptic feedback was implemented to signify the start and finish of a game mode, button activations, incorrect button presses and attempting to change game mode amidst play. The intensity and duration of feedback is variable depending on the performed action, e.g., incorrect actions trigger more pronounced feedback, whereas haptics accompanying valid button activations are light and short-lived.*

Evaluation of VHB Game – Phase 3 User Study: A third phase of evaluation was conducted to evaluate the user experience of the updated VHB version (VHB v2). The purpose of this evaluation was to examine if user impressions and experience improved after incorporating visual, audio and haptic guidance features in the VHB game design as identified in the Phase 2 user study. This study was conducted in the university VR lab, where users played the VHB (v2) accumulator game using a Meta Quest headset. They then completed the questionnaire. The VR headset was not connected to a display monitor so that experimenters did not have any visual feedback to guide users; users were solely guided by visual, audio and haptic game features. Twenty users (8 male, age range 33.8±9.1, 18 right-handed), not part of the phase 1 and 2 evaluation, were recruited for the phase 3 evaluation upon providing informed consent. As users completed identical questionnaires in both user studies, we compared mean scores corresponding to VHB (v1) and VHB (v2) for the different game attributes, and the comparisons are depicted in Figure 10. Green lines and *s denote significant inter-version score differences, as conveyed by a two-sample t -test. The physical BATAK is perceived as being significantly better than VHB with respect to engagement, ease of play, button control and extent of focus (i.e., being less distracting), while the VHB version was seen to facilitate better light tracking. While scores like VHB (v1) were observed for engagement and ease of light tracking, significantly higher scores for VHB (v2) were noted for the ease of play, button control and extent of focus attributes.

These results confirm that the incorporated features considerably enhanced game play, and consequently, user experience. Some qualitative user comments provided below are also reflective of these observations.

- *I liked the simplicity of the game; it was very clear in what was required from the player, and it was easy to play.*
- *It seemed well designed and immersive but generally feels more like a test than a game.*
- *It was clear and easy to manage, the recognition of hand movements was precise. The buttons were very low for me as 6ft, I had to bend down.*
- *The overall experience has been good but I would love to have more time to play the game.*
- *Certainly, immerses you and with future visual advancement (unreal engine), it will be life-like and will blur lines between real and virtual.*

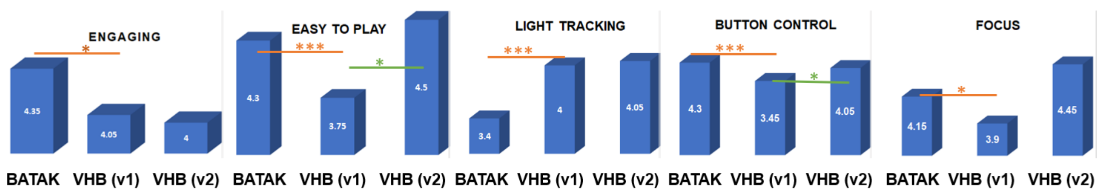

Figure 10. Mean user scores corresponding to multiple attributes of the BATAK and VHB

Going forward, the VHB game design needs to be extended so that all three game modes involve multiple levels of difficulty and can engage elderly population at the comfort of their residence. The VHB game can be further extended to different demographics such as sportspersons, dementia and stroke patients to train tasks repetitively over extended time-periods to achieve outcomes superior to traditional approaches.

Discussion

The study was driven by an interest in understanding how VR application can be designed to improve physical and cognitive acuity of users. By adopting an iterative design science research approach (Hevner & Chatterjee 2010), the study illustrates the steps involved in design, development and evaluation of a gamified VR application to engage users in activities that can demonstrate their physical and cognitive abilities. It also investigates customized design that can address the diverse needs of vulnerable communities by involving health experts in aged care and rehabilitation. In addition, this study also highlights various design principles for a VR application that addresses users' needs. The staged research process used in the iterative design and evaluation of the application following Peffers et al. (2007) and Sonnenberg and Vom Brocke (2012), aided in the identification of the requirements of a VR application design and the formulation of the design principles following iterative evaluation (Venable et al. 2012). The design principles developed in this study will contribute towards designing a new gamified VR application specifically to improve users' physical and/or cognitive acuity. The iterative evaluation process in this study contributes to three important design principles which are contributions to theory and practice and are outlined below.

DP1: Principle of User Accessibility: User accessibility focuses on the design of the artifact to cater to diverse users. ISO 9241-171 (2008b) defines accessibility as: the usability of a product, service, environment or facility by people with the widest range of capabilities. This well-known principle is even more significant while designing an artifact like a gamified VR application for health and clinical use, where the target users and their needs must be the focal point (Thach et al. 2023). For example, feedback from health experts and end-users resulted in developing a customizable lightboard for users with limited physical capability or reach as illustrated in Figure 6. Inclusive design is particularly important when we target elderly users with various impairments (e.g. motor skills) (Kim et al. 2018). VR experience differs from the traditional web and mobile applications in terms of input using hand gestures and controllers, head mounted output display devices, interaction mechanisms and field of view. On the other hand, the advantage with VR games is the flexibility they offer, as users can play them at their preferred physical location. Vlahovic et al., (2023) highlight the importance of ensuring a comfortable, accessible, and safe VR experience for users and Heilemann et al., (2021) provide accessibility guidelines for VR games. To further contribute to the existing studies, DP1 aims to address the diverse capabilities, requirements, and preferences of VR users with the principle of user accessibility.

DP2: Principle of Sensory Cueing: The principle of sensory cueing promotes rendering an immersive user experience and user abilities in the design of the artifact. This principle is critical for two reasons. First, it plays a crucial role in creating a sense of presence and immersion in the virtual environment. Cueing is defined as using temporal or spatial stimuli to facilitate the initiation and continuation of a movement (Palacios-Navarro et al. 2016). Visual, auditory, olfactory cues as well as haptic feedback are different ways to improve the rendering of an immersive user experience (Heilemann et al. 2021). Sensory cueing designed in a VR environment can engage the user to perform any specific motor activity and hence is recommended as a promising design principle to enable easy use of the VR application. Incorporation of tool tips at the fingertips, radial view display, 3D audio and haptic feedback were identified in this study based on the feedback from experts, gamers and common users. Second, as different senses can be used to understand the user's perception of the task at hand, VR devices can be used to record users' sensory and physical movements. For example, measuring hand movements and tracking eye movements captured by the VR devices provide valuable feedback about the visual and physical acuity of the user. Hand dexterity, visual-flow cues, spatial, temporal and kinematic parameters are various ways in which VR sensory cueing can support learning the physical and cognitive abilities of its users (Palacios-Navarro et al. 2016). However, there is always a need to consider users with motor disability and sensory disability while designing the application using DP2 - the principle of sensory cueing.

DP3: Principle of Cognitive Loading: The principle of cognitive loading mainly emphasizes the rendering of a facile environment for the users to play, by adhering to the prescribed usability principles. It is important to consider visual complexity, motion sickness, and colors used in the design of the VR game to reduce cognitive and information overload, as users rely on their visual and cognitive perception while playing the game in a virtual environment (Gasques, et al. 2021). Reducing cognitive load is a well-known design principle in the field of Human Computer Interaction (HCI) as it is the level of concentration used to retain information in the short-term memory (Hollender et al. 2010). Providing tool tips in audio and text format was found to help users with diverse needs to reduce their cognitive load. Radial view display and change in view with a click also helped users to reduce the visual complexity and motion sickness while they walk around the virtual environment. Haptic feel and feedback are another way to reduce their cognitive overload while they immerse themselves with the touch and feel in the VR environment. Young et al., (2020) identified that there is no significant cognitive load when operating in the virtual reality environment, but it is the role of the designers and researchers to make sure users' cognitive load is minimized as proposed by DP3, to introduce VR applications in our daily activities and specially in the context of healthy ageing. To add on, while designing the game, equal importance should be given towards designing a parallel *performance analytics* application that can capture user movements and give them continuous feedback about their performance and related improvements for extended engagement and motivation.

Thus, the study meets the relevance by enabling the VHB game to measure the physical and cognitive abilities of users by capturing their hand movements, speed and memory of users. The study meets the rigor by contributing the above design principles to build theory towards the design of future VR applications (Heilemann et al. 2021). DSR guidelines enabled an interactive development of the VR application. Limitations of this study is the need to test the application by elderly community to understand their experience while they play. To test among elderly community, there is a need to ensure that the design is comprehensive enough and that we have enough support to ensure that the participants are free from any risks while testing the VR application. The study opens the prospects for further research in the field of virtual human interaction and health science. Future work will involve tailoring the VHB game design to suit the requirements of specific demographics such as older adults, sportspersons, people living with dementia and stroke patients, and validating with these communities.

Conclusion

This research paper presents the design, development, and evaluation of a Virtual Human Benchmark (VHB) VR game that stimulate the BATAK reaction test to measure the physical and cognitive acuity of players. The study demonstrates the steps involved in designing the artifact based on the user needs, iterative evaluation and re-design of the artifact following the DSR guidelines. Expert opinions as well as qualitative and quantitative user opinions comparing the physical BATAK game with VHB (v1) revealed the following advantages: 1) VHB game can induce positive outcomes in sports and health areas; 2) VHB game is engaging and interactive, 3) VHB game enables easier light tracking as compared to the physical BATAK. However, usability issues were noted, which hampered overall user experience. These issues were addressed via the implementation of visual, auditory, and haptic user guidance features in VHB (v2). A second study with an independent user group revealed that VHB (v2) usability and user experience were considerably superior to VHB (v1). Based on the findings, the study contributes to the theory by proposing three design principles. The principle of user accessibility (DP1), the principles of sensory cueing (DP2) and the principle of cognitive loading (DP3) contribute to the future design of VR games and development of VR applications.

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