On performing vestibular damage assessment and therapy using virtual reality: lessons learned

Ambika Bansal*, Gita Mikal+, Shehzad Surya+, Laurence R. Harris*, Michael Jenkin*
*Centre for Vision Research, York University, Toronto, Canada,
+Physiomobility Health Group, North York, Canada
(abansal2, jenkin, harris)@yorku.ca

***Abstract*—Virtual and augmented reality-based devices have been proposed for a range of assessment and treatment tasks, but how well are they accepted by clinicians and their patients? To investigate this question a prototype VR-based tool was developed for vestibular damage assessment and treatment. Designed to be used primarily within an in-person clinical setting, this tool was developed with the long-term goal of also supporting in-home independent and supervised treatment. Mock treatment and assessment sessions were held with non-clinical patients and the operational and patient experiences evaluated qualitatively through post-session questionnaires. Participants found the process engaging although there were concerns over hygiene, especially in light of the COVID pandemic. Clinicians felt that a VR- or AR-based approach could be effective, especially if it engaged patients in supervised, at-home exercises.**

***Index Terms*—VR-based evaluation and treatment**

I. Introduction

Virtual reality (VR) is an oft-promised tool that will revolutionize the treatment of physical and societal ills. This promise can be traced back to the mid 1990's and the work on the use of VR to treat acrophobia (fear of heights) as described in [1]. This early study of one undergraduate student patient utilized 1995 VR technology with physical cues as part of a de-sensitization process to treat acrophobia. Since this early work, there have been a number of efforts to incorporate VR to deal with phobias (e.g., arachnophobia [2], public speaking [3], flying [4], acrophibia [5]), see [6] for a recent review), rehabilitation treatment following injury (e.g., [7], [8]), and for physical training generally. Although a number of studies have appeared, as identified in [9], "the quality and sample size of the various studies is far from ideal". Beyond the efficacy of VR-augmented treatment, an additional concern is the acceptability of VR-based treatment by both the patient and the clinician. For many of the VR-augmented treatments described in the literature, an existing non-VR-augmented treatment exists. Even if a VR-based treatment might lead to an improved long-term outcome, acceptance of the treatment requires acceptance by the patient and the clinician. This is the concern we address here.

When VR was first proposed for clinical treatment in the mid 1990's, the infrastructure for VR-based treatment was quite involved. Rothbaum's system [1] required high end computing hardware, specialized tracking hardware that was sensitive to external factors, and an expensive head mounted display. This technological solution was coupled with physical props to enhance the sensation of immersion. VR technology has advanced considerably since the mid 1990's and as a consequence the infrastructure required to deliver VR-based treatment has been simplified considerably. Sophisticated "all-in-one" VR systems now exist and indeed now dominate the VR home market. Such systems would seem almost ideally suited for deployment for in-clinic and remote treatment. The technology is easily deployed and supported remotely. But will clinicians and patients accept the technology?

Research has found a positive response from healthcare professionals when using VR applications in clinical settings, although the perceived usefulness is directly related to the ease of using the platform and whether there will be sufficient support for learning the technology [10]. Although this study only implemented a video prototype of the VR experiences, not the actual VR experiences themselves. VR has also been found to have the potential role of assisting nurses in health promotion and managing disease, although for use with older adults, similar reports of prior preparation was emphasized [11]. Some studies that have actually tested older adults and found that using VR is acceptable, and feasible for healthy adults [12], dementia patients [13], and stroke patients [14]. Although in a hospital setting, there are still concerns around safety and storage. Hilton and colleagues [14] observed that "therapists would not adopt a new strategy [for stroke rehabilitation] without evidence-based research to demonstrate that it was effective...". Clearly there exist open questions that remain around the acceptance of VR technology in clinical settings.

The remainder of this paper is organized as follows. Section II reviews vestibular function, its evaluation and treatment. Section III describes the use of VR-augmented evaluation and treatment within the traditional assessment and treatment process. Sections IV describes the process followed to characterize patient and clinician acceptance of the technology. Finally, Section V summarizes the results found and suggests directions for future work.

II. Vestibular function: evaluation and treatment

The vestibular system is a very ancient sense but one whose full impact we still don't fully understand. It is morphologically developed and functioning even before birth [15]. As well as being involved in low-level automatic responses such as the

The financial support of the VISTA project is gratefully acknowledged.

2023 IEEE Gaming, Entertainment, and Media Conference (GEM) | 979-8-3503-1540-0/23/$31.00 ©2023 IEEE | DOI: 10.1109/GEM59776.2023.10389963

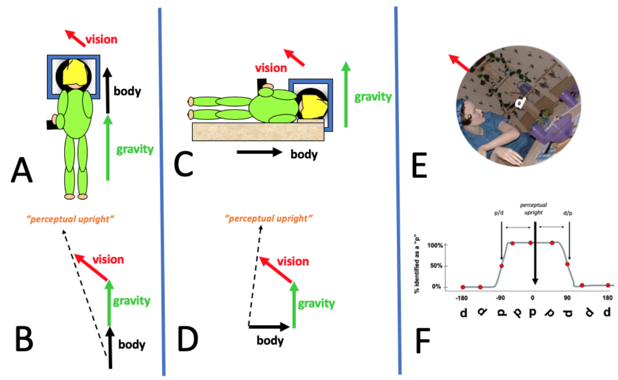


Fig. 1. The OChaRT test. Observers view a screen arranged so that nothing outside the circular display (E) is visible either when upright (A) or lying on one side (C). The display (E) shows a highly polarized scene with a clear upright. Superimposed on this image is the probe character (p/d) and the participant's task is to simply respond as to whether the character looks more like a "p" or a "d". By plotting the percentage of time, one interpretation is chosen (F), and the points of ambiguity can be determined. The perceptual upright is defined as being midway between these orientations.

(a) Reference object view (b) Target object view

Fig. 2. The Find Target task. The participant first fixates the reference object (a), and then once this object is selected, must move their viewpoint to fixate on the target object (b). The possible locations of the target object are defined by the clinician and are set to exercise the participant's head motion and thus their vestibular system.

vestibulo-ocular [16] and vestibulo-spinal [17] reflexes, it is also involved in many higher functions [18] such as forming cognitive maps of space [19] and of one's own body [20]. Thus, damage to or malfunctioning of this system can have multiple consequences.

Vestibular impairment occurs as a consequence of a range of different conditions, including stroke [21]–[23], concussion [24] and head trauma [25]. Dizziness and related vestibular-like issues are also reported with no obvious physiological cause, especially in the elderly [26]. Vestibular impairment can be extremely debilitating, and can impair normal daily activities. Dizziness and low vestibular function can impact mobility, leading to falls and fall-related injuries. One-third of older adults in Canada will fall at least once each year and one-quarter will experience a fall-related injury [27]. Monitoring and rehabilitation of vestibular function is essential for quality of life and reducing long-term medical costs.

A. Assessment

Vestibular function can be assessed through any of its functions, such as eye movement control, balance, or self-motion perception [28]. In 2006, Dyde, Jenkin and Harris [29] developed a quantitative measure for estimating the relative importance of the main factors that determine the perceptual upright using visual probes presented to an observer while they were in different body positions. By separating upward sensation signaled by the bodily, gravity and visual cues, they were able to quantify their individual contributions. This tool, known as OChaRT (the Oriented CHAracter Recognition Test), has proven successful in estimating a subject's perceptual upright and the relative contributions of vision, gravity and the body to that estimate (e.g., [30]–[32]). The OChaRT test uses a character – p/d – the identity of which depends on its orientation. The perceptual upright is defined as the orientation of that character at which it is most unambiguously identified. To find this orientation, the points of greatest ambiguity are found (at which the character is equally likely to be identified as either interpretation) from which the orientation of least ambiguity can be deduced (Figure 1).

The perceptual upright can be modeled as the sum of three vectors corresponding to the orientation signaled by visual cues, gravity cues and the internal representation of the body [29]. By testing in at least two body roll orientations, the relative lengths of the vectors corresponding to the contributions of the vision, gravity and the body can be calculated using simple geometry. The direction of the perceptual upright can be modeled as the sum of three vectors corresponding to the directions of upright signaled by the visual display, gravity, and the orientation of the body from which the relative lengths of the vectors can be calculated, corresponding to the relative contributions of body, gravity and visual cues to upright. Vestibular function can be characterized by the strength of the gravity cue in this computation.

B. Treatment

Various rehabilitation therapies have been proposed to help restore normal vestibular function (see [33], [34]) and are generally recommended in order to enable such individuals to return to their normal daily lives [35]. Many of the required therapies involve repetitive exercises that encourage adaptation to the underlying vestibular system damage. Monitoring such exercises, and in particular, ensuring that patients perform such exercises between visits to therapists is critical to improving patient outcome. Lack of adherence to these assigned exercise regimes usually comes down to two reasons: patient anxiety from lack of guidance or boredom from repetitiveness of exercises [36]. Gamification of therapeutic exercises can alleviate boredom by providing guided and personalized treatment progression from the safety and comfort of a patient's home [37], [38], but even here, monitoring and refining of assigned exercises is critical to the outcome of the patient's recovery.

In order to enable patients' engagement in vestibular exercises at home, rehabilitation tasks are designed to be straightforward and to utilize material that is readily available in the home. For example, a task might require a patient to fixate playing cards that have been secured to the walls of a patient's home and then to make head motions that cause the patient to move their head so that it is directed at different cards. Although in-clinic presentations of these exercises can be standardized – the cards placed at well identified and well-known locations – this is unlikely to be the case when the exercise is set up by the patient in their own home. Thus a critical problem in rehabilitation is that the patient may not do the exercises assigned, and if they are done, they may not be executed correctly.

VR-based home exercises can be based on these 'traditional' exercise tasks. This leverages the clinicians' and patients' experiences with these tasks and provides a straightforward approach to integrating the VR-based tasks into the patients' treatment. [39] describes an all-in-one VR infrastructure enabling vestibular stimulation exercises that can be carried out either under direct supervision within a clinical setting or between clinical visits at the patient's home. The same infrastructure also provides a vestibular function assessment tool. The system utilizes commodity virtual reality hardware (the Lenovo Daydream Mirage Solo) and software tools (Unity) integrated with a cloud-based system providing control of rehabilitation tasks as well as data collection from individual patient sessions. This environment is sufficient to provide VR versions of standard rehabilitation exercises, assessment of vestibular function through the OChaRT test, and a record of head motions during the exercise. As the Lenovo Daydream Mirage provides network connectivity specifics of a given exercise, and participant performance including head motion during the exercise, are easily recorded and transmitted to the clinic for processing.

The work here concentrated on two common exercises – find target and choose target – that require the participant to move their head in a controlled manner by looking at targets positioned in space. The physical world version of this task has the participant seated looking at a normal room with a small number of targets taped to the room's walls.

1) Find Target: The Find Target exercise is a head movement exercise treatment in which the participant moves their head from a neutral position indicated by the reference object to point towards a location indicated by a target object. In the pen-and-paper exercise, target objects can be represented by playing cards or pieces of paper with writing either held in the clinician's hand or taped to a wall. The target may be horizontally, vertically, or diagonally displaced relative to the neutral head position, depending on the type of hypofunction and treatment goals. When the participant is comfortable repeating this activity for 1–2 minutes, the task can be made more complex. For example, the object can be placed against a visually complex background, such as patterned wallpaper or a dynamic background such as a television screen. In the clinic, participants progress from a seated position, to seated on a stability ball, to standing, to standing on soft surfaces or on one leg.

The VR version of this task is illustrated in Figure 2. Here the user is placed in a virtual environment and the reference target (a 3d placeholder) is rendered directly in front of the participant. The participant fixates on the reference object and presses a button using a wand when the reference object is fixated. At this point, the reference object is replaced by a target object at some displacement relative to the reference object. The participant then moves their head around the space until the target is fixated and their head is pointing to the target and then presses a button using the wand to indicate that they have localized the target. The participant's task is to move their head to find a target positioned somewhere in space. The location of the target(s) is pre-selected based on the treatment.

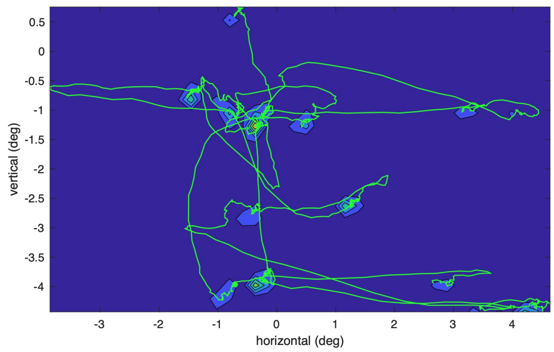
(a) Reference view (b) Target view

Fig. 3. The choose target task. The participant first fixates on the reference object (a), and then once this object is selected, they must move their viewpoint to choose the target object (b). A distractor object is also presented in the virtual space. The possible locations of the target object are defined by the clinician and are set to exercise the participant's head motion and thus their vestibular system in specific ways.

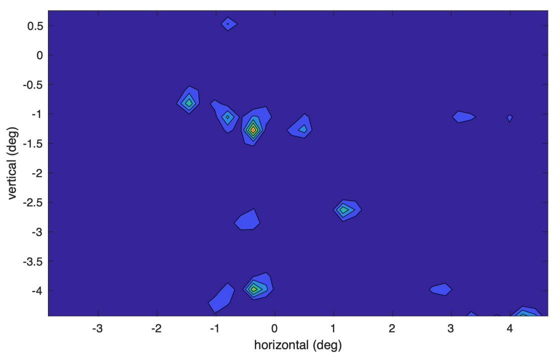
2) Choose Target: Choose Target adds a second target to the Find Target task described above (Figure 3). Adding another target allows a participant to practice moving their eyes and head between the two directions. Ideally, the additional target is placed just inside their periphery so they can move their focus between the two such that only a single target is clear at any given time. These objects can be separated horizontally, vertically or diagonally relative to one another.

These target exercises allow for one target to be placed directly in front of the patient, and the other, for example, to appear over their left shoulder or over their right shoulder, all at eye level. While seated the patient looks from one target to another. Only one of the two targets is the same as the reference target which is the one that must be looked at. The other target is a distractor. As the displacement between the two targets is increased the patient must make larger and larger head motions to bring the correct target into view. The controlled direction of separation between the two test targets forces the patient to make head motions in the desired directions when performing the task. As with the Find Target exercise, once the patient is sufficiently comfortable carrying out the exercise seated and with the targets against a neutral background, they may progress to gradually more complex backgrounds, or to standing on one or both feet, or seated on a stability ball.

The VR version provides the opportunity to personalize the environment and choose the objects to be displayed. The VR version of the task also provides considerable information about the actions of the patient. Quantitative information about time taken, velocity of the patient's head motion, and fixation performance are recorded. One critical advantage of the VR-based solution is that quantitative data concerning head motion



(a) Head motion



(b) Motion heat map

Fig. 4. Tracked head orientation during the find target task. In (a) multiple trials are shown, each with a track that begins approximately at (0,0) and moves to the orientation of the target to be found. (b) shows a heat map of the dwell time time at each head orientations over multiple trials.

is recorded "automatically" as a consequence of the VR nature of the rendering. For example, for the find target task, head directions can be recovered and a heat map of head orientation dwell times can also be recovered (Figure 4).

III. Managing users and treatments

As modern HMDs like the Lenovo Mirage Solo incorporate an integrated computer with WIFI access, this connectivity can be leveraged to control treatment plans on individual devices even when they are remote from the clinic. Patients register a given HMD with a cloud-based server and clinicians manage their patients and their patients' treatments using a web application. The front-end of the application was created using the Angular web application framework and the Angular Material component library. The back-end server exchanges and stores data to and from the front end and HMDs. Full implementation details can be found in [39].

IV. Patient, experimenter and clinician acceptance

In order to better understand patient and clinician acceptance of the technology as part of the standard evaluation and treatment process associated with treating vestibular disorders, a set of normal individuals were assessed and then treated as though they were clinical patients, and the participants and clinicians experiences recorded throughout the mock clinical treatment. Assessment and evaluation/treatment followed standard clinical procedures as would be followed by patients reporting vestibular conditions. The experiment and procedures described in this paper were approved by the Ethics Board of York University (certificate number e2018-334). All participants signed an informed consent form before participating. Participants received an $200 honourarium for participating in the study.

Participants. Ten participants (5F, 5M; mean age 44.2 years, SD $\pm$ 17.7)participated in this study. All participants had normal or corrected-to-normal vision and were screened for any vestibular disorders.

A. Procedure

Assessment and treatment took place in a total of six sessions, including the intake session, with each session approximately one week apart.

Session 1: Participants gave informed written consent, and filled-out a pre-screen questionnaire to assess whether they had any prior vestibular disorders. Once the pre-screen was completed, an in-person screening for any vestibular impairment was administered. This included five simple exercises to assess their vestibular function. All participants were able to complete these exercises with no significant sway, loss of balance, or symptoms of dizziness, indicating no vestibular impairment. This initial assessment follows the traditional intake assessment of vestibular patients. Following this assessment, which in part confirmed the normal vestibular condition of the participants, the remaining evaluation and treatment utilized the HMD-based technology described above.

First, as a measure of baseline vestibular function, participants began their first session by completing the OChaRT assessment (see Figure 1). To parse out the relative contributions of vision, gravity, and the body to their perceptual upright, subjects performed the first half of the OChaRT task sitting upright, and the second half lying on their left side. They then moved on to the two training tasks: the 'Find Target' and 'Choose Target' tasks (described above). Both tasks were comprised of 100 trials. The 'Find Target' task started with objects that were 16-degrees apart for the first three sessions and progressed to 32-degrees apart for the last three sessions. For the 'Choose Target' task, participants started with three possible targets to choose from and progressed to four possible targets for the last three sessions. At the end of each training session, participants were given a questionnaire to fill out to assess their experience with the HMD-based assessment and treatment. This questionnaire included both questions on a five-point Likert scale as well as open form questions.

Sessions 2-5: These sessions consisted of the Find Target and Choose Target tasks. After completing these tasks the

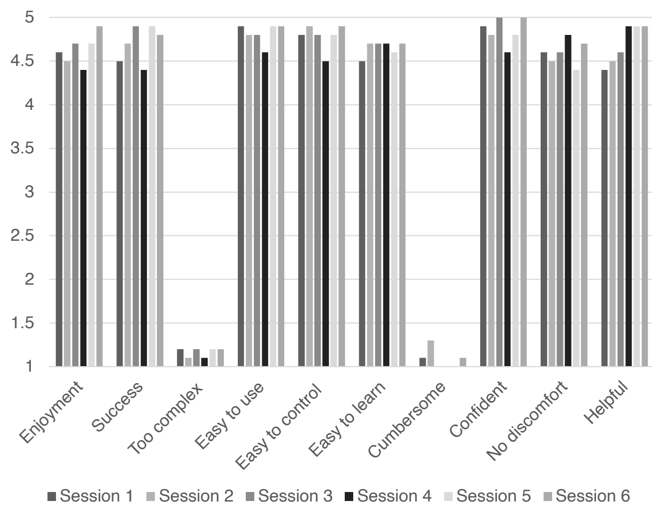


Fig. 5. Average participant scoring on a Likert Scale 1: Strongly disagree 5: strongly agree for the six sessions

participant completed the questionnaires as in Session 1.

Session 6: As in sessions 1-5, Session 6 consisted of the Find Target and Choose Target tasks. After completing these tasks the participant completed the questionnaires and then a final evaluation using OChaRT was performed.

B. Acceptance

The five-point Likert scale captured the participant's impression of the simulated treatment that they received over ten dimensions (Figure 5). In general, participants found the assessment and treatment infrastructure easy to use, control and learn. They enjoyed the experience, were successful in using the hardware, confident in its use, felt that the exercises would be helpful in treatment, and reported no discomfort. They did not find the system complex or cumbersome to use.

Following each session the participant and experimenter completed separate questionnaires that sought to capture the experience as observed by the individuals involved. Both the participants and the experimenter found the technology easy to use. There were some concerns with the display fogging up, especially when the participant had to move their head from one target to another. The experimenter had concerns with tasks that took too long (e.g., the OCHarT procedure) and with difficulties in configuring the server to deploy the appropriate treatments to the hardware.

Once all of the sessions were completed, the two clinicians who supervised the study were interviewed to identify successes and failures of the approach. They reported that the basic approach was sound and that it would have potential use outside of the clinic itself. One of the clinicians observed that "Depending on the patient's level of comfort with technology as well as the need to assess how safe their particular home environment is, defines suitability for in-home treatment. As long as these factors can be safely managed this would be a great tool for in-home treatment." The other concurred, "This is an excellent tool for home use as well as using it for remote communities with limited access to vestibular therapy. The application of this program requires considerations being given to safety, physical functional and cognitive ability of the client."

There were concerns related to the ease of use of the server technology to deliver treatments both in the clinic and remotely in some future system: "Simplify the set up process to be intuitive, improve trouble shooting, improve visuals to be able to add real life backgrounds."

One issue that was raised by both clinical testers related to the acceptability of the technology given the COVID pandemic and heightened sensitivity to the cleanliness of the hardware. One observed that "Hardware sanitization needs to be improved as it was one major concern and barrier during the testing period." The other clinician concurred, observing that "Given the heightened sensitivity to sanitisation and cleanliness in the post COVID world, using materials for the VR headset which could be easily cleaned would make a huge difference in the willingness of patients to use this technology and improve it's acceptance in the wider market."

V. Discussion

Vestibular rehabilitation, like many rehabilitation tasks, provides patients with exercises in the clinic that the patient is to complete on their own, at home. The exercises are repetitive, and not always the most enjoyable. As the exercises are intended to be transferred to the patient's home, a common approach is to use easily obtained and inexpensive infrastructure (e.g., a deck of cards and some tape in the case of many vestibular rehabilitation exercises). Obtaining quantitative results with such infrastructure is difficult, a problem that becomes even more difficult when the exercises are performed at home. The lack of such evaluation as well as the difficulty in ensuring that the at home exercises are being performed as reported by the patient, impact patient treatment and the rehabilitation process.

VR/AR-based systems have the potential to address both of these issues. The VR/AR hardware collects data (e.g., head motion data) that can be extremely helpful in the assessment and treatment process, and the self-contained nature of commodity VR/AR hardware enables remote tuning and reporting from the devices when they are deployed in the clinic and at home. Simulated patients and clinicians find the technology easy to use and anticipate that advanced versions of the technology will provide more exciting and engaging visual displays as well as provide a more clinician-friendly remote control and reporting mechanism. One key concern that was highlighted by the clinicians is the difficulty of providing effective sanitization with head-mounted displays. Even though in this study the display technology was disinfected between users it can be difficult to communicate this to users. Although it was never reported, another possible concern for patients with vestibular disorders using VR could be cybersickness. Ongoing work is exploring how non-contact displays could be used to provide the same in clinic and remote support for vestibular rehabilitation while providing a more easily verified sanitized technology.

References

[1] B. O. Rothbaum, L. F. Hodges, B. Kooper, D. Opdyke, J. S. WIllford, and M. North, "Virtual reality graded exposure in the treatment of acrophobia: a case report," *Behavior Therapy*, vol. 26, pp. 547–554, 1995.

[2] A. Miloff, P. Lindner, W. Hamilton, L. Reuterskiöld, G. ANdersson, and P. Carlbring, "Single-session gamified virtual reality exposure therapy for spider phobia vs. traditional exposure therapy: study protocol for a randomized controlled non-inferiority trial," *Trials*, vol. 17, p. 60, 2016.

[3] P. Premkumar, N. Heym, D. J. Brown, S. Battersby, A. Sumich, B. Huntington, R. Daly, and E. Zysk, "The effectiveness of self-guided virtual-reality exposure therapy for public-speaking anxiety," *Frontiers in Psychiatry*, vol. 12, 2021.

[4] A. Gottlieb, G. M. Doniger, Y. Hussein, S. Noy, and M. Plotnik, "The efficacy of a virtual reality exposure therapy treatment for fear of flying: A retrospective study," *Frontiers in Psychology*, vol. 12, 2021.

[5] E. Rimer, L. V. Husby, and S. Solem, "Virtual reality exposure therapy for fear of heights: Clinicians' attitudes become more positive after trying VRET," *Frontiers in Psychology*, vol. 12, 2021.

[6] S. Riches, S. Pisani, L. Bird, M. Rus-Calafell, P. Garety, and L. Valmaggia, "Virtual reality-based assessment and treatment of social functioning impairments in psychosis: a systematic review," *Int. Rev. Psychiatry.*, vol. 33, pp. 337–362, 2021.

[7] K. I. Ustinova, J. Perkins, W. A. Leonard, and C. J. Hausbeck, "Virtual reality game-based therapy for treatment of postural and co-ordination abnormalities secondary to TBI: a pilot study," *Brain Inj.*, vol. 28, pp. 486–495, 2014.

[8] J. Keller, I. Štětkárová, V. Macri, S. Kuhn, J. Petioky, S. Gualeni, C. D. Simons, V. Arthanat, and P. Ziber, "Virtual reality-based treatment for regaining upper extremity function induces cortex grey matter changes in persons with acquired brain injury," *J. NeuroEngineering Rehabil.*, vol. 17, p. 127, 2020.

[9] J. Qian, D. J. McDonough, and Z. Gao, "The effectiveness of virtual reality exercise on individual's physiological, psychological and rehabilitative outcomes: A systematic review," *Int. J. Environ. Res. Public Health*, vol. 17, p. 4133, 2020.

[10] A. Halbig, S. K. Babu, S. Gatter, M. E. Latoschik, K. Brukamp, and S. Von Mammen, "Opportunities and challenges of virtual reality in healthcare – a domain experts inquiry," *Frontiers in Virtual Reality*, vol. 3, 2022.

[11] M. M. Saab, M. Landers, D. Murphy, B. O'Mahony, E. Cooke, M. O'Driscoll, and J. Hegarty, "Nursing students' views of using virtual reality in healthcare: A qualitative study," *Journal of Clinical Nursing*, vol. 31, p. 1228–1242, 2022.

[12] S., Syed-Abdul, S. Malwade, A. A. Nursetyo, M. Sood, M. Bhatia, D. Barsasella, M. F. Liu, C.-C. Chang, K. Srinivasan, M. Raja, and Y.-C. Li, "Virtual reality among the elderly: a usefulness and acceptance study from taiwan," *BMC Geriatrics*, vol. 19, p. 223–310, 2019.

[13] S. Karaosmanoglu, S. Rings, L. Kruse, C. Stein, and F. Steinicke, "Lessons learned from a human-centered design of an immersive exergame for people with dementia," *Proc. ACM Human-Computer Interaction*, vol. 5, p. 1–27, 2021.

[14] D. Hilton, S. Cobb, T. Pridmore, J. Gladman, and J. Edmans, "Development and evaluation of a mixed reality system for stroke rehabilitation," in *Advanced Computational Intelligence Paradigms in Healthcare 6. Virtual Reality in Psychotherapy, Rehabilitation, and Assessment*, S. Brahnam and L. C. Jain, Eds. Heidelberg: Springer, 2011, p. 193–228.

[15] A. E. Ronca, F. Bernd, L. L. Bruce, and J. R. Alberts, "Orbital spaceflight during pregnancy shapes function of mammalian vestibular system," *Behavioral Neuroscience*, vol. 122, p. 224–232, 2008.

[16] J. Szentágothai, "The elementary vestibulo-ocular reflex arc," *J. Neurophysiol.*, vol. 13, p. 395–407, 1950.

[17] F. Karmali, A. D. Goodworth, Y. Valko, T. Leeder, R. J. Peterka, and D. M. Merfeld, "The role of vestibular cues in postural sway," *J. Neurophysiol.*, vol. 125, pp. 672–686, 2021.

[18] E. R. Ferrè and L. R. Harris, *Vestibular Cognition*. Amsterdam: Brill, 2017.

[19] N. L. Dallal, B. Yin, A. S. T. Nekovářá, and W. H. Meck, "Impact of vestibular lesions on allocentric navigation and interval timing: The role of self-initiated motion in spatial-temporal integration," *Timing & Time Perception*, vol. 3, p. 269–305, 2015.

[20] E. R. Ferrè and P. Haggard, "The vestibular body: Vestibular contributions to bodily representations," *Cognitive Neuropsychology*, vol. 3294, 2016.

[21] S. Glasauer, M. Dieterich, and T. Brandt, "Neuronal network based mathematical modelling of perceived verticality in acute unilateral vestibular lesions - from nerve to thalamus and cortex," *Journal of Neuroscience*, vol. 265, pp. 101–112, 2018.

[22] H. O. Karnath and D. Broetz, "Understanding and treating 'pusher syndrome'," *Phys. Ther.*, vol. 83, pp. 1119–1125, Dec 2003.

[23] A. Saj, J. Honore, T. Bernati, Y. Coello, and M. Rousseaux, "Subjective visual vertical in pitch and roll in right hemispheric stroke," *Stroke*, vol. 36, pp. 588–591, Mar 2005.

[24] B. A. Alsaheen, L. O. M. A. Mucha, S. L. Whitney, J. M. Furman, C. E. Camiolo-Reddy, M. W. Collins, M. R. Lovell, and P. J. Sparto, "Vestibular rehabilitation for dizziness and balance disorders after concussion," *Journal of Neurologic Physical Therapy*, vol. 34, pp. 97–93, 2010.

[25] Y. O. Herishanu, "Abnormal cancellation of the vestibuloocular reflex (vor) after mild head and or neck trauma," *Neuro-Ophthalmology*, vol. 12, pp. 237–240, 1992.

[26] C. P. Hobeika, "Equilibrium and balance in the elderly," *Ear, Nose & Throat Journal*, vol. 78, pp. 558–566, Aug 1999.

[27] S. Canada, "Senior's falls in canada: Second report," 2014. [Online]. Available: http://www.phac-aspc.gc.ca/seniors-aines/publications/public/injury-blessure/seniors_falls-chutes_aines/index-eng.php

[28] M. Fetter, "Assessing vestibular function - which tests, when," *J. Neurology*, vol. 247, pp. 335–342, 2000.

[29] R. T. Dyde, M. Jenkin, and L. R. Harris, "The subjective visual vertical and the perceptual upright," *Exp. Brain Res.*, vol. 173, pp. 612–622, 2006.

[30] M. Barnett-Cowan, R. T. Dyde, S. H. Fox, E. Moro, W. D. Hutchison, and L. R. Harris, "Multisensory determinants of orientation perception in parkinson's disease," *Neuroscience*, vol. 167, pp. 1138–1150, Jun 2010.

[31] R. Dearing and L. R. Harris, "The contribution of different parts of the visual field to the perception of upright," *Vision Research*, vol. 51, pp. 2207–2215, Oct 2011.

[32] L. R. Harris and M. Jenkin, "The effect of blur on the perception of up," *Optometry and Vision Science*, vol. 91, pp. 103–110, 2014.

[33] C. D. Hall, S. J. Herdman, S. L. Whitney, S. P. Cass, R. A. Clendaniel, T. D. Fife, J. M. Furman, T. S. Getchius, J. A. Goebel, N. T. Shepard, and S. N. Woodhouse, "Vestibular rehabilitation for peripheral vestibular hypofunction: an evidence-based clinical practice guideline: from the american physical therapy association neurology section," *Journal of Neurologic Physical Therapy*, vol. 40, p. 124, 2016.

[34] B. I. Han, H. S. Song, and J. S. Kim, "Vestibular rehabilitation therapy: Review of indications, mechanisms, and key exercises," *Journal of Clinical Neurology*, vol. 7, pp. 184–196, 2011.

[35] S. A. Telian and N. T. Shepard, "Update on vestibular rehabilitation therapy," *Otolaryngologic Clinics of North America*, vol. 29, pp. 359–371, 1996.

[36] O. Khan, I. Ahmed, J. Cottingham, M. Rahhal, T. N. Arvanitis, and M. T. Elliott, "Timing and correction of stepping movements with a virtual reality avatar," *PLOS ONE*, vol. 15, no. 2, p. e0229641, feb 2020. [Online]. Available: https://dx.plos.org/10.1371/journal.pone.0229641

[37] G. Saposnik and M. Levin, "Virtual Reality in Stroke Rehabilitation," *Stroke*, vol. 42, no. 5, pp. 1380–1386, 2011.

[38] M. K. Holden and T. Dyar, "Virtual environment training: A new tool for neurorehabilitation," *Neurology Report*, vol. 26, no. 2, pp. 62–71, 2002.

[39] A. Adjindji, C. Kuo, G. Mikal, L. R. Harris, and M. Jenkin, "Vestibular damage assessment and therapy using virtual reality," in *Proc. 7th Int. Conf. on Augmented Reality, Virtual Reality and Computer Graphics*, Lecce, 2020.