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ORIGINAL RESEARCH

Contextual sensory integration training via head mounted display for individuals with vestibular disorders: a feasibility study

Anat V. Lubetzky[a], Jennifer Kelly[b], Zhu Wang[c], Marta Gospodarek[d], Gene Fu[b], John Sutera[a,b] and Bryan D. Hujsak[b]

[a]Department of Physical Therapy, Steinhardt School of Culture, Education and Human Development, New York University, New York, NY, USA; [b]Vestibular Rehabilitation, New York Eye and Ear Infirmary of Mount Sinai, New York, NY, USA; [c]Future Reality Lab, Department of Computer Science, Courant Institute of Mathematical Sciences, New York University, New York, NY, USA; [d]Department of Music and Performing Arts Professions, Steinhardt School of Culture, Education and Human Development, New York University, New York, NY, USA

ABSTRACT

Purpose: Virtual reality (VR) interventions can simulate real-world sensory environments. The purpose of this study was to test the feasibility of a novel VR application (app) developed for a Head Mounted Display (HMD) to target dizziness, imbalance and sensory integration in a functional context for patients with vestibular disorders. Here we describe the design of the app as well as self-reported and functional outcomes in vestibular patients before and after participating in vestibular rehabilitation using the app.

Material and methods: Our app includes a virtual street, airport, subway or a park. The clinician controls the visual and auditory load including several levels of direction, amount and speed of virtual pedestrians. Clinicians enrolled 28 patients with central (mild-traumatic brain injury [mTBI] or vestibular migraine) and peripheral vestibular disorders. We recorded the Simulator Sickness Questionnaire, Visual Vertigo Analogue Scale (VVAS), Dizziness Handicap Inventory (DHI), Activities-Specific Balance Confidence Scale (ABC), 8-foot up and go (8FUG) and Four-Step Square Test (FSST) before and after the intervention.

Results: Within the 15 patients who completed the study, 12 with peripheral hypofunction showed significant improvements on the VVAS ($p = 0.02$), DHI ($p = 0.008$) and ABC ($p = 0.02$) and a small significant improvement on the FSST ($p = 0.015$). Within-session changes in symptoms were minimal. Two patients with mTBI showed important improvements, but one patient with vestibular migraine, did not.

Conclusion: HMD training within increasingly complex immersive environments appears to be a promising adjunct modality for vestibular rehabilitation. Future controlled studies are needed to establish effectiveness.

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KEYWORDS
Vestibular rehabilitation; HMD; HTC Vive; virtual reality; sensory integration; balance

➤ IMPLICATIONS FOR REHABILITATION

- Virtual Reality allows for gradual introduction of complex semi-real visual environments.
- Within VR training patients can re-learn to maintain balance when presented with a sensory conflict in a safe environment.
- Head Mounted Display training appears to be a promising adjunct modality for vestibular rehabilitation.
- Portability and affordability of the hardware and software enhance the potential clinical outreach.

The vestibular system provides sensory information regarding self-motion, head position and spatial orientation [1]. This information then helps with gaze stability, head stability and postural control. Damage to the vestibular system at the peripheral organs (inner ear) or central organs (vestibular nuclei and their connections to the brainstem, cerebellum and cortex) could lead to imbalance and loss of orientation in space, often manifested as dizziness [1]. Postural control is a complex perceptual-motor process that is known to include: (1) sensation of position and motion from the visual, somatosensory, and vestibular systems; (2) processing of that sensory information to determine orientation and movement; and (3) selection of motor responses that maintain or brings the body into equilibrium [2]. Individuals with vestibular disorders may employ substitution strategies by over-relying on visual or somatosensory input in order to maintain balance during stance or gait [3]. Recently, hearing substitution, i.e., over-reliance on auditory cues for balance, has been proposed as well [4]. Inefficient sensory substitution and reduced ability to reference the vestibular system for orientation are explanatory mechanisms for the functional complaints of people with vestibular disorders which often involve dizziness, imbalance and heightened anxiety within complex, busy and noisy environments [5]. Therefore, one goal of vestibular rehabilitation is to facilitate a proper sensory integration process within different tasks, such as, sitting, standing or walking. Of particular importance in this process is the gradual introduction of complex visual environments such that patients can learn (or re-learn) to maintain spatial orientation when presented with a sensory conflict. Practicing this with graded and controlled exposure could also allow for a decrease in the associated emotional aspect tied to the negative experience of dizziness

CONTACT Anat V. Lubetzky anat@nyu.edu Department of Physical Therapy, Steinhardt School of Culture, Education and Human Development, New York University, 380 2nd Avenue, 4th floor, New York, 10010, NY, USA

and imbalance. Therefore, virtual reality (VR) programmes have been proposed as viable intervention strategies for patients with vestibular disorders [6].

Virtual reality programmes can simulate real-world environments. This allows for specific impairments, such as dizziness, imbalance or anxiety, to be trained within a functional context [7,8]. The control and customisation over programme design allows for gradual exposure to environmental stimuli in a safe environment that is controlled, measurable, and reproducible [9]. Indeed, virtual reality rehabilitation has been shown to be more effective than traditional rehabilitation with regards to physical outcomes for patients with vestibular dysfunction [10]. Patients performing balance exercises in VR have reported more enjoyment, less fatigue after the activity, and a perception of less difficulty compared with traditional exercises [7]. A recent systematic review suggested that VR rehabilitation programmes are more effective than traditional rehabilitation, most likely because of increased excitement of participants, increased adherence, and increased cognitive load within the VR environment [10]. Within a virtual environment, the practiced task is more similar to the real-world conditions, thus transfer to daily living is more likely. For example, the Computer Assisted Rehabilitation Environment (CAREN) is a VR system for assessment and rehabilitation of balance. The CAREN has been shown to be effective in various populations [11,12], yet the cost of installing, maintaining, and running a CAREN has been estimated to be over $1 million [11]. Other affordable off-the-shelf gaming products (such as the Wii [13] or Kinect [14]) have been shown to be effective for balance rehabilitation. These, however, do not allow control over specificity of the environments or gradual manipulation of the sensory load [8].

We created a clinical application (app) for the HTC Vive Head Mounted Display (HMD) to provide a graded way for patients to experience complex sensory environments in a functional yet safe context. An important early step when designing a new clinical app is to identify barriers for practical use of the new technology in the clinical settings [15]. Glegg and Levac identified barriers and facilitators for clinical implementation of VR interventions [16]. They suggested that an integrated research approach should engage clinicians throughout the research process, involving them in the decision making and addressing site-specific institutional barriers to technology [16]. Implementation science has been defined as "the scientific study of methods to promote the systematic uptake of research findings and other evidence-based practices into routine practice" [17]. While randomised controlled trials are needed to establish effectiveness, the implementation science framework calls for descriptive clinical studies earlier in the research pipeline in order to identify barriers and increase external validity of later effectiveness studies. Implementation studies typically employ mixed quantitative-qualitative designs, identifying factors that impact clinical translation across multiple levels, including patients, clinicians and the overall facility. The purpose of this study was to test the feasibility and usability of our VR app within a vestibular rehabilitation clinic. In a previous report we discuss user feedback from patients and clinicians [18]. Here we expand the description of the app and describe symptoms, self-reported and functional outcomes in patients before and after participating in vestibular rehabilitation *via* the app.

Materials and methods

System design

Virtual environments

Our system has four primary scenes: airport, subway, city, and park.

The airport scene has a 3D graphics model of an airport terminal which simulates a real airport (see Figure 1) with people walking around at different speeds, and an aeroplane flying over the terminal randomly, in a range of 50–58 s. Sounds include footsteps from the surrounding people, sounds of aeroplanes, ambient sounds of people chatting, and announcements recorded from a real airport. The clinicians control the walking directions, amount and speed of the virtual pedestrians and can choose the participants' position to be in the middle of the great hall, on the second floor, or by the stairs. The clinician can enable the added visual stimulus of planes taking off, advertisement posters on the walls of the terminal, patterns on the floor, etc. Sounds can be modified between three levels of intensity: no sound, ambient sound and complex sound.

This scene was developed based on patients' stories, such as:

- "I am able to travel but, in busy airports I sit in a wheelchair … (because) people (are) coming from front and back and all the sounds … ."
- "when I walked into the airport lobby and there was a patterned floor. I almost fell over."

The subway scene (Figure 2) is a 3D model of a real subway station in New York City. It has the same crowd generation module as the airport scene that generates people walking in groups on the platform, mezzanine, and staircase. Subway trains are active on four rails with each rail having a subway car pass by every 35–50 s. Similar to the airport scene, the subway ambient sounds contain noises, including people chatting, announcements recorded from Grand Central station, footsteps and running trains. Options for the clinicians include manipulations of the quantity, speed and walking directions of the virtual pedestrians; choice of the initial position for participants from the platform (middle or corner by the stairs), or the mezzanine; change of sound level between no sound, ambient sound and complex sound. Clinicians can also enable or disable passing trains, the textures and colours on the floor, pillars, and walls.

The subway scene was developed based on patients' stories, such as:

- "I don't feel comfortable standing on the platform, I feel like I will fall over."
- "I don't take the subway (because) there are too many people and I am afraid of falling onto the track if someone bumps into me."

The city scene simulates a street which contains moving vehicles, buildings at randomly generated heights and pedestrians (see Figure 3). Complex sounds include footsteps, car horns honking, a jackhammer, and sirens. Ambient sounds include people chatting and city rumbling sounds, mainly caused by traffic. The clinicians can enable/disable cars; manipulate the quantity, speed, walking directions of the virtual pedestrians; manipulate the quantity and speed of cars on the street; the textures and colours of the buildings and cars; four levels of lighting condition; and sound level between no sound, ambient sound, and complex sound.

Some feedback statements provided by patients during the development phases of the city scene were:

- "This feels like a mild version of the outside experience."
- "I feel uneasy with the rapid change of light to dark … it's like (I experience) in the cinema."

The ball & park scene has a square-shaped park in the middle of a city and tennis ball machines launching balls towards

Figure 1. A screenshot from the aeroplane scene. Here the participant is standing in the middle of the great hall. Specific features enabled include: pedestrians walking in multiple directions, patterned floor, signs and an aeroplane.

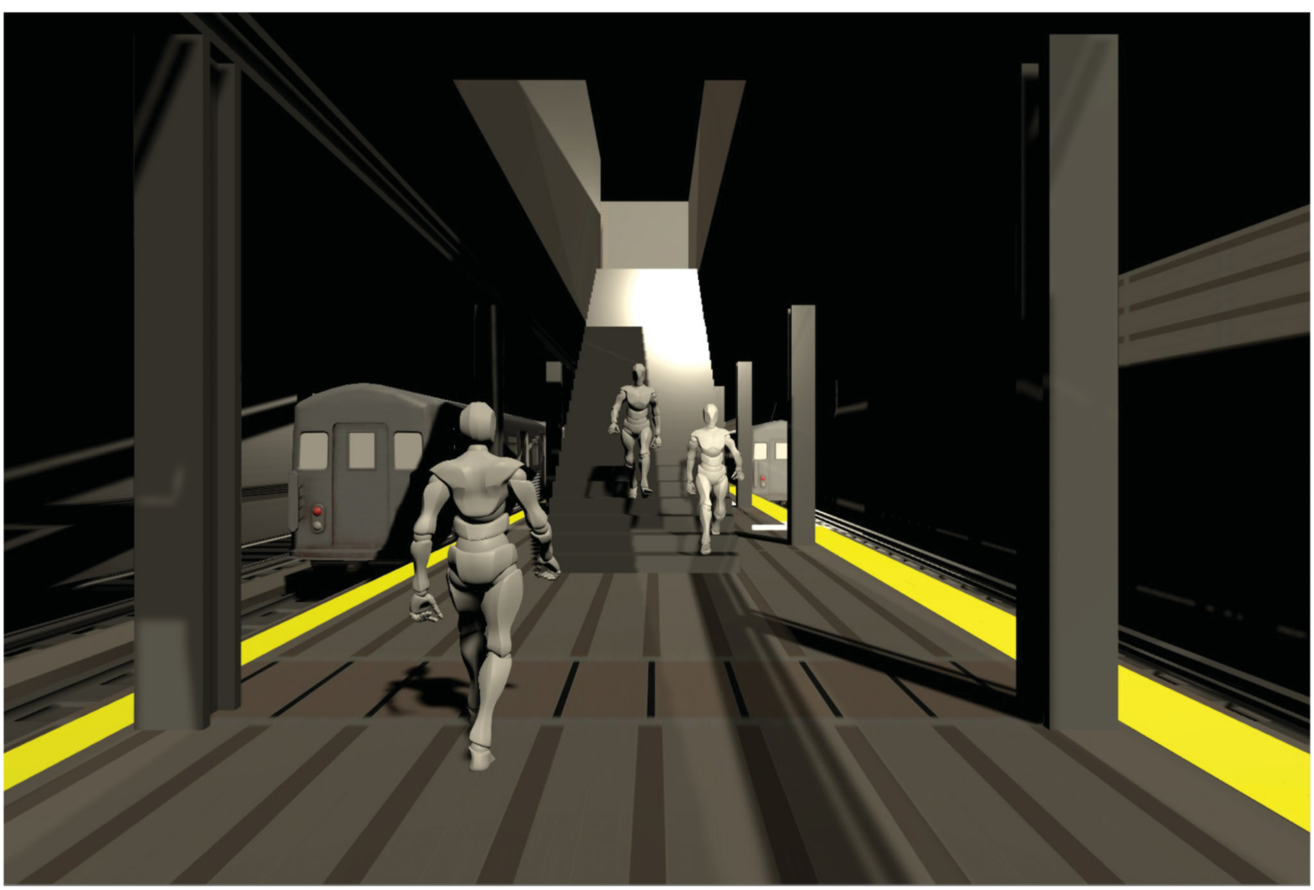

Figure 2. A screenshot from the subway scene. Here the participant is standing in the middle of the platform. Specific features enabled include: pedestrians walking in two directions, textures and colour on the floor and trains.

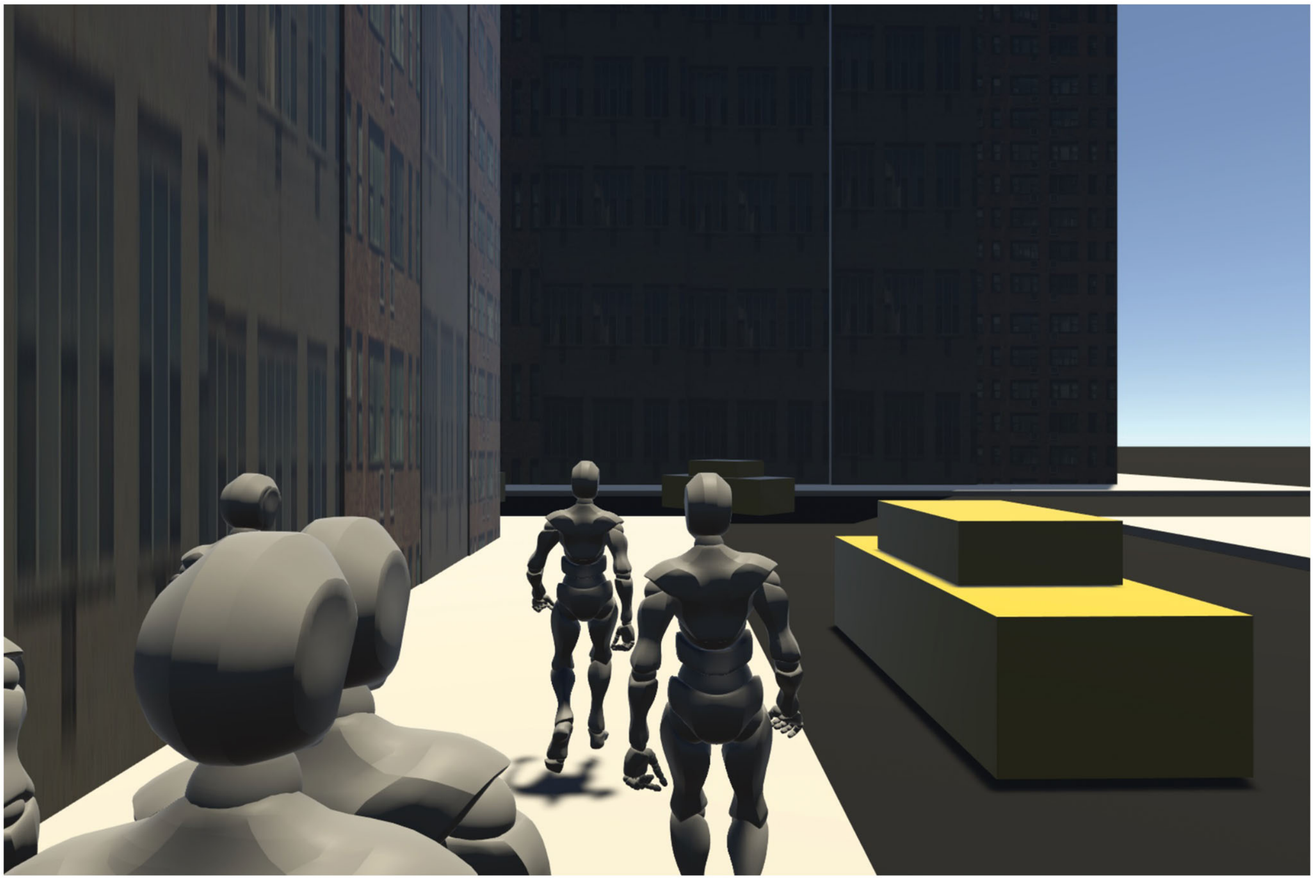

Figure 3. A screenshot from the city scene. Specific features enabled include: pedestrians walking in one direction, patterned buildings and moving cars.

participants (see Figure 4). The participants stand in the middle of the park and needs to avoid the ball by moving their centre of mass outside of their base of support and back to regain their balance. The clinician can choose how many balls will be activated at the same time (from 0 to 3) and from which direction(s), centre, right or left. Once the ball shooting machines are activated, every two balls from each ball machine have a randomised interval between 2 and 4 s. The Clinicians have similar choices for modifying pedestrians, lighting, number of cars etc., as in the city scene. Sounds include footsteps, vehicles passing by, chatter, and bird sounds mixed into the ambient sound. In addition, the user can hear the flying effect of the balls as the balls approach their head.

Some feedback provided by patients during the development phases of the ball & park scene:

- "If I dodged like that in open space, I would feel dizzy, but I had no problem doing it within the scene!"
- "I think that would be a great therapy for making me move my head … If you played with where it goes"(meaning the ball should come from different places and aim at different directions)

The 4 environments provide visual-spatial characteristics that a variety of patients with vestibular disorders report having difficulty adjusting to. Namely, the airport scene is a large enclosed space, the subway scene is a confined enclosed space and the city scene is an open space. Similar to the various sunlight conditions in a real open-air environment, the city and ball & park have four levels of lighting ranging from 0 to 3. The brightest level simulates the sunlight at noon on a sunny day, the second level provides a cloudy day or morning sunlight, the third level represents dim lighting, and the fourth level represents a dark scene.

User interface and content control

To make the app clinically usable, we created an intuitive user interface (UI) with sliders, and checkboxes, for the clinicians to choose scenes, change levels of visual or auditory stimuli, and enable/disable graphics effects or contents. With the "Scene" slider, the clinicians can choose between the airport, subway, city, or ball & park scenes. See Figure 5(A) for a detailed description of the UI and 5b for the controller options.

Hardware setup

Our system is implemented in C\# language using Unity Engine version 2018.1.8f1 (64-bit) (Unity Technologies, San Francisco, CA). It uses SteamVR as the runtime and OpenVR as the API to get full compatibility with all major VR display platforms such as Oculus Rift and HTC Vive. The HTC Vive and Oculus Rift both have a resolution of 1080×1200 for each eye, a 90 Hz refresh rate, and 110 degrees field of view. The HTC Vive minimum specifications are Intel Core i5-4590 or AMD FX 8350 for CPU, 4GB for RAM, NVIDIA GeForce GTX 1070/Quadro P5000 or AMD Radeon\Vega 56 for GPU, and Windows 8.1 or later for operation system. The minimum requirements of the Oculus Rift are Intel i3-6100 or AMD FX4350/Ryzen 3 1200 for CPU, 8GB for RAM, NVIDIA GTX 1050Ti or AMD Radeon RX 470 for GPU (alternatively, NVIDIA GTX 960 or AMD Radeon R9 290), and Windows 10 for OS. Our lab setup is an Alienware laptop 15 R3 running Windows 10 with 8GB RAM, Intel i7-7820HK CPU, and Nvidia GTX 1080 Max-Q GPU. During

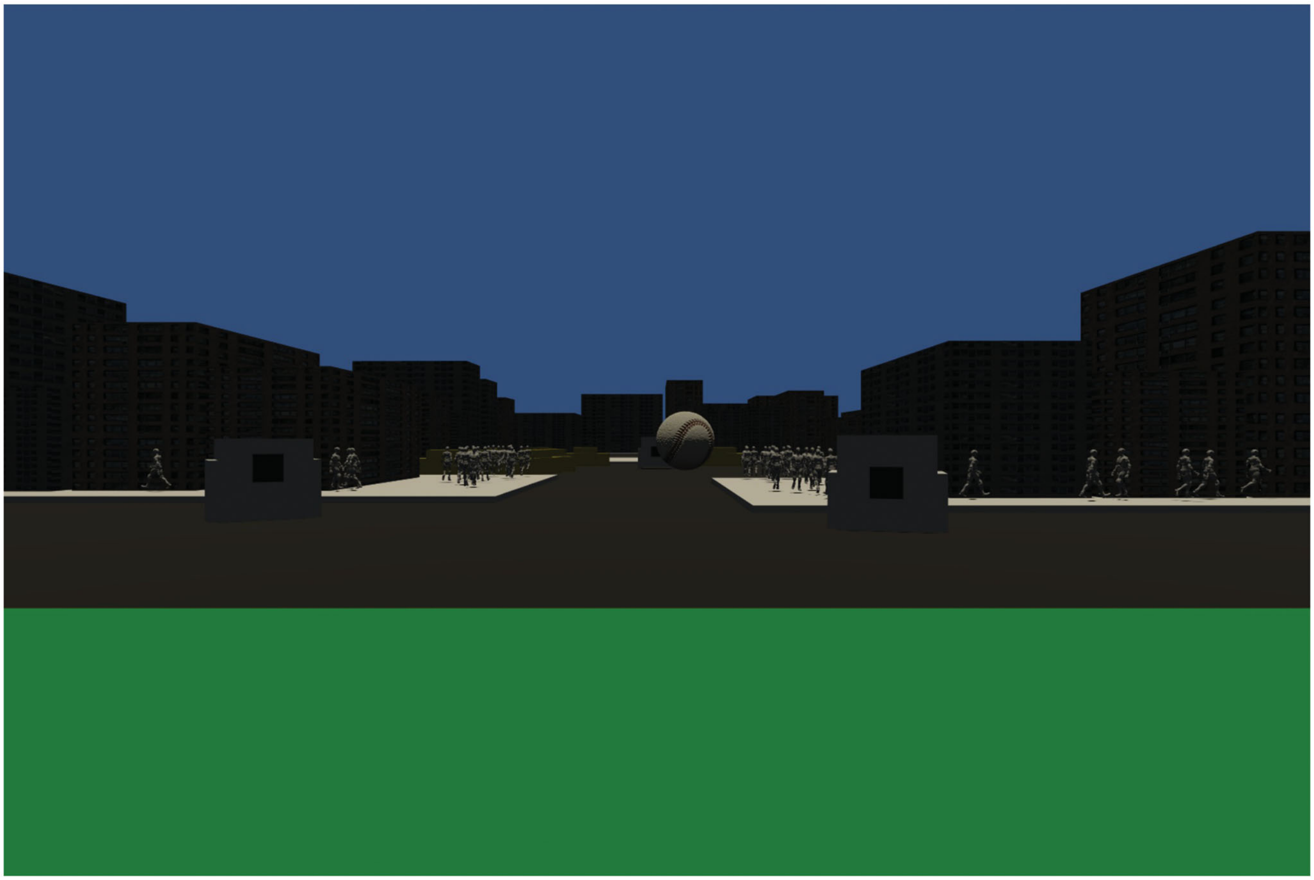

Figure 4. A screenshot from the park scene. Three ball shooting machines are positioned in front of the participant but here only 1 is active. Additional features enabled include pedestrians walking in multiple directions.

our test, the platform runs on the highest level of graphics contents can work at over 120 fps with either HTC Vive or Oculus Rift. This study was conducted with the HTC Vive.

Procedure

This study was designed as a descriptive in-clinic usability trial with repeated measures of the participants before and after vestibular rehabilitation that included training with the app. All participating clinicians went through two training sessions with the VR app and were provided with a short checklist regarding maintenance of the laptop/use of the app. The checklist included the following tips: keep the laptop battery 50% charged, plug in Vive headset first then start the app, unplug vive first if system needs to be restarted. Included participants could have been new or existing patients at the vestibular rehabilitation clinic of the XXXXXXXXXX with central or peripheral vestibular disorders. Training with the VR app was performed for 10–20 min as a part of the patients' typical 30–45-min intervention sessions. Other components of the rehabilitation programme included patient education and review and progression of home exercise programme including, but not limited to gaze stability and static and dynamic balance tasks. This study was approved by the XXXXXXXXX Institutional Review Board and all participating patients signed a written informed consent prior to commencing the study procedures.

Outcome measures

The 15-item Kennedy Simulator Sickness Questionnaire [19] was administered at least twice every session (beginning and end, more if necessary). Questions begin with "are you experiencing any" and then cover different symptoms such as fatigue, general discomfort, blurred vision, dizziness etc. Items are scored as "none" (0), "slight" (1), "moderate" (2) or "severe" (3). The Visual Vertigo Analogue Scale (VVAS) is a self-reported questionnaire where a participant rates their visual vertigo on a 10 cm line in 9 different visually challenging environments [20,21]. A VVAS severity score is calculated as the sum of measurement on each item divided by the number of items (9) and then multiplied by 10 [20]. A severity score of 0 indicates no dizziness and a score of 90–100 indicate severe dizziness. The Dizziness Handicap Inventory (DHI) is a 25-item questionnaire used to evaluate self-perceived disability related to dizziness [22]. Items are scored no (0), sometimes (2), or yes (4). A score of 0–30 is classified as mild disability, 31–60 as moderate, and 61–100 as severe [23]. The minimal clinically important difference has been identified as 18 points [22]. The Activities-Specific Balance Confidence scale (ABC) is a 16-item, self-reported questionnaire in which participants rate their balance confidence when performing daily activities on a scale of 0–100%. Zero indicates no confidence and 100 indicates completely confident [24]. Scores of less than 67% indicate fall risk in patients with vestibular disorders [25]. The 8-Foot Up and Go (8FUG) test is a timed test that requires the participant to stand up from a chair, walk 8 ft, turn around a cone on the floor, walk 8 ft back and sit down. A cut-off of 8.5 s was identified as increased fall risk in community dwelling older adults [26]. The Four-Square Step Test (FSST) is a multidirectional stepping test of dynamic balance and coordination used to determine an individual's falls risk. Participants are asked to step over 4 canes on the floor in a clockwise then counter clockwise direction while being timed [27]. In community dwelling adults over the age of 65, fall

Figure 5. (A) User interface (UI); (B) controller options. Controlling the pedestrians' walking speed and the speed of the cars in the city is done by modifying "Speed" between 0 (static) and 3. The speed of the aeroplane in the airport scene, and the speed of the subway train in the subway scene are both fixed. Walking paths of pedestrians are controlled by "Walking Direction" (0: front to back, 1: back to front, 2: horizontal or 3: all). The quantity of pedestrians is selected by "Walking Amount" (0 to 3). "Sound Level" changes the sound from completely silent (0) to ambient (1) or complex (2). "Car Amount" controls the number of cars on the street of the city scene and the ball & park scene. Zero will generate no cars, and 1-3 are for low, medium and high quantity accordingly. "Level" adjusts the difficulty level of the balls in the ball & park scene from 1 centre ball (0) to random generation of any 1 ball to 2 randomly generated balls (4). On the other scenes, 'level' changes the position of the participant in the scene, for example from the ground level to the mezzanine in the airport or subway. The checkboxes help users to choose if they want to enable or disable the details of the secondary graphics contents in the airport, city and subway scenes. "Light," "Colour" and "Material" checkboxes respectively control the lighting in the scenes, colours and materials on the buildings, floors, cars, walls, posters, etc.

risk was indicated by a score $>$ 15 s [27]. Whitney et al. determined a cut off score of 12 s for patients with vestibular disorders [28].

Sample

Over the 16 months of the study, 6 physical therapists enrolled 28 patients from the vestibular rehabilitation clinic. A total of 13 patients dropped out of the study after 1–4 sessions due to the following reasons: Anxiety (1 patient), at physician's request (1), concern regarding symptoms (1), other orthopaedic injuries that happened after enrolment (2) did not return to therapy (7) and patient completely symptom-free after 1 session (1). Diagnoses of patients who dropped out included unilateral or bilateral peripheral hypofunction, or vestibular migraine. Fifteen patients completed the study, of whom 1 had vestibular migraine (30-year-old male, duration of symptoms 29 months), 2 had mild traumatic brain injury (mTBI, 2 men, average age 27.5, average duration of symptoms 54.5 months) and 12 had unilateral peripheral hypofunction (5 women, mean age 57, SD = 13.5, Mean duration of symptoms = 34 months, SD = 11). See Table 1 for additional co-morbidities.

Statistical analysis

Descriptive statistics were used for all outcomes. Wilxocon signed-rank tests were used for a paired non-parametric comparison

Table 1. Co-morbidities and other self-reported factors that may affect rehabilitation outcomes in the sample.

Co-morbidity	N of patients with peripheral hypofunction	N of patients with mTBI/migraine
Prior vestibular rehabilitation	6	NA
Migraine	4	2
Prior head trauma	3	2
Taking vestibular suppressing medications	1	NA
Self-reported anxiety	2	1
Self-reported depression	2	NA
Diabetes	3	NA
Glaucoma/cataracts	3	NA
Oculomotor impairment	4	2
Hearing loss	6	1
History of falls	3	NA
Neuropathy	2	NA
Pain	NA	1
Arthritis	1	NA
Other neurological disorders	1	NA
Cardiac disorder	3	1
Respiratory disorder	1	NA
GI/metabolic disorder	2	NA
Immunological disorder	1	NA
Orthopaedic surgery, fractures, osteoporosis, assistive device	NA	NA

Values represent the number of participants who reported a specific co-morbidity.

Table 2. Simulator Sickness Questionnaire (SSQ) total score on first and last session per diagnosis. Best score is 0 (no symptoms), worse score is 60 (severe symptoms on all items).

	1st Session Pre	1st Session Post	Last session Pre	Last session Post
Peripheral Hypofunction (Mean (SD))	4.75 (4.22)	4.17 (5.06)	3.25 (3.41)	2.5 (3.63)
mTBI (Mean (SD))	13 (11.3)	18.5 (13.4)	14 (1.4)	16 (9.9)
Vestibular Migraine	7	6	8	9

between performance on VVAS, DHI, ABC, 8FUG and FSST before and after intervention among the peripheral hypofunction group. Spearman's correlations were used to determine whether differences in self-reported outcome measures correlated with age, chronicity in months or symptoms at baseline for the peripheral hypofunction group. Visual comparison was done for the two patients with mTBI and 1 with vestibular migraine.

Results

Intervention

The minimum number of sessions was 3, maximum 8 (Average 6 sessions, SD = 1.3). The clinicians worked with patients within the most challenging level that did not induce exacerbation of the patients' symptoms to more than moderate on the SSQ. If symptoms increased, the clinicians were instructed to scale back the scene's complexity and provide a rest break. A starting position for exercises using the VR app was based upon the patient's ability to hold a position without loss of balance in order to effectively handle the VR perturbations and could include sitting supported or unsupported or standing with or without support. Progress could include modifying the base of support or the support surface, head movements, walking within a 5 ft × 5 ft area, and turning. Progress was guided by the patients balance abilities (comfort in a position without loss of balance), symptoms (as described above) and any reports of fear or anxiety within an environment. Time per scene varied between patients (typically 60–120 s but could go up to 5 min per scene with patients who were not symptomatic). The number of scenes also varied according to rest breaks needed. The choice of scene was made based on the functional needs of the patients. For a protocol example see our companion paper [18].

Symptoms

Total SSQ scores per diagnosis appear in Table 2. Overall patients with central vestibular disorders were more symptomatic than those with peripheral hypofunction. Changes after a virtual reality session were minimal (within a single session as well as comparing first session to last).

Self-reported outcomes

See Figure 6 for changes on self-reported outcomes per diagnosis. Patients with peripheral hypofunction showed significant improvements on all self-reported measures: VVAS ($p = 0.02$), DHI ($p = 0.008$), and ABC ($p = 0.02$). The average improvement was 19.8 cm on the VVAS (SD = 25.3), 13.8 points on the DHI (SD = 17.3) and 8.3% on the ABC (SD = 9.03). Five patients improved by more than the minimal clinically important difference (i.e., > 18 points) on the DHI [22]. Both patients with mTBI improved on the VVAS (by 7 or 8 cm). One patient improved on the DHI (by 20 points) and the ABC (by 30%) and the other did not change. The 1 patient with vestibular migraine had worse VVAS (by 10 points), similar DHI (4 points lower) and similar ABC (about 6% lower). There were no significant correlations between changes in outcomes and age, chronicity or symptoms at baseline (all Rs ≤ 0.4).

Functional outcomes

The average 8FUG in the peripheral hypofunction group was 6 s prior to intervention (mean 5.9 s, SD = 0.99) and did not change (mean 6.15, SD = 1.19). 8FUG stayed the same for 1 patient post-concussion (5 s) and improved from 8.7 s to 6.87 s for the other. This patient was the only one who performed above the cut-off for fall risk at baseline [26]. 8FUG also stayed the same for the patient with vestibular migraine (5.9 s pre and 5 s post). The FSST (Figure 7) was significantly better post intervention in the peripheral hypofunction group ($p = 0.015$) with a small average change

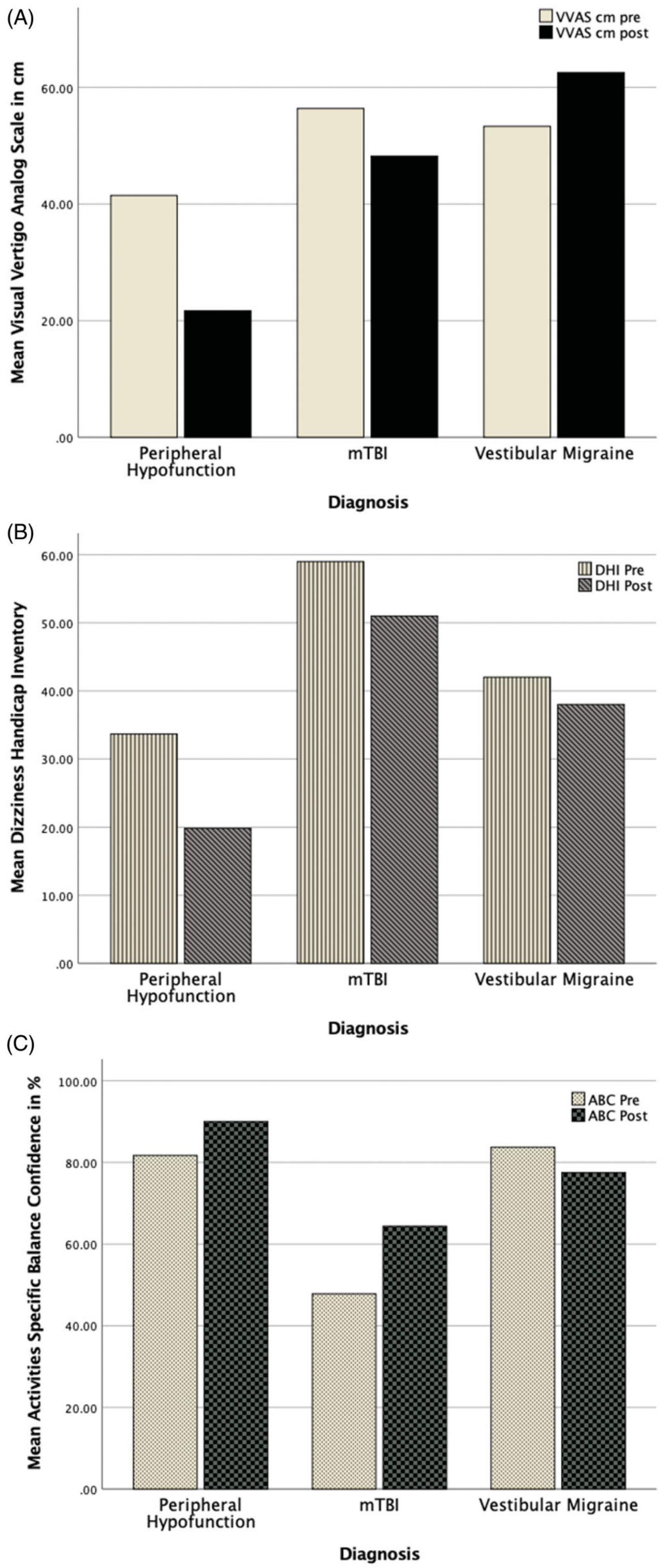

Figure 6. Summary of changes in self-reported outcome measures: Visual Vertigo Analogue Scale (VVAS, A), Dizziness Handicap Inventory (DHI, B) and Activities-Specific Balance Confidence (ABC, C). The value for the peripheral hypofunction group represents average across 12 patients, for the mTBI group, average across 2 patients and for the vestibular migraine the actual value from 1 patient.

of 1.69 s (mean pre = 9.7, SD = 2; mean post = 7.96, SD = 1.76). Only one patient was close to fall risk (14.76 s) [27] at baseline and improved to 10 s following the intervention. Another patient improved from 8.6 s at baseline to 3.56 post intervention. The 2 patients with mTBI started at 11.19 s (improved to 9.39) or 10.81 (improved to 9.28). The patient with vestibular migraine did not change his FSST time (8 s).

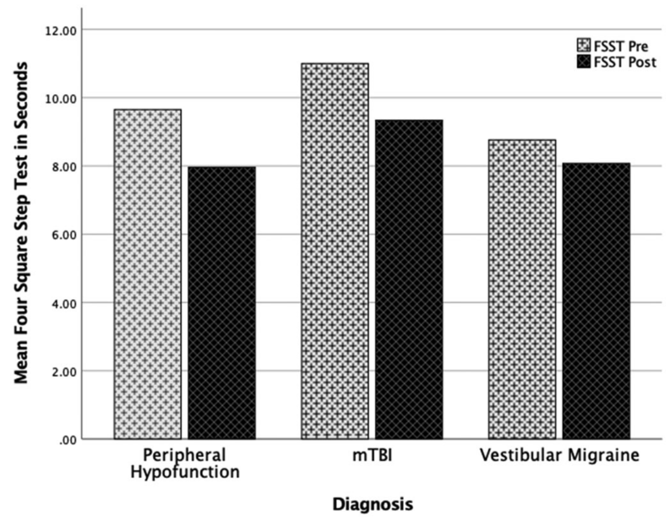

Figure 7. Summary of changes in the Four-Square Step Test (FSST). The value for the peripheral hypofunction group represents average across 12 patients, for the mTBI group, average across 2 patients and for the vestibular migraine the actual value from 1 patient.

Discussion

In this descriptive feasibility study, 15 patients with peripheral or central vestibular disorders went through training with a novel virtual reality app as part of their traditional vestibular rehabilitation. Most patients appeared to have benefitted from the intervention despite the chronicity of their disorder and having several co-morbidities that may negatively affect rehabilitation outcomes [6]. One patient with vestibular migraine had no gains and another with peripheral hypofunction had self-reported worsening of symptoms and was discharged with a plan to address other co-morbidities.

Massetti et al. raised a concern regarding motion sickness or cybersickness that could result from the use of VR especially when the visuals are moving and the user is standing still [15]. They mentioned that cybersickness should be carefully examined, particularly when working with people with vestibular disorders whose primary complaint is dizziness and imbalance in busy environments. In our study there was minimal increase in symptoms for patients with peripheral hypofunction. In addition, both patients with mTBI started as very symptomatic and yet both reported large improvements. This suggests that despite the concern of cybersickness with VR programmes, having high symptoms at baseline is not necessarily a prediction of failure, particularly if symptoms do not worsen during training. Note that both patients with central disorders continued to use VR in rehabilitation beyond the end point of the study and showed further gains. Therefore, 8 sessions may not be the ideal number for all patients.

Implementation science requires a solid grounding in theory and the involvement of interdisciplinary research teams in the design of a new intervention [17]. Our theoretical framework utilised the following principles to optimise function in busy visual environments, facilitate use of residual vestibular function, and perhaps central adaptation for better sensory integration. First, we wished to create a safe environment for learning [29], to remove any fear or anxiety with the hope to create mental habituation and combat any "fear avoidance" behaviour. Second, the adaptive nature of the human nervous system makes it imperative that we train individuals in salient conditions, as close as possible to those commonly encountered during daily activities [30]. This is particularly important for balance training which is known to be task-specific [31,32]. Training in a real-life context should theoretically create better transfer to daily function. In addition, we had patients practice a task as a whole where we begin with a simple setup and gradually build more complex environmental conditions. The app also creates mild and gradual increases in visual flow. This gradual exposure may have led to habituation in some patients. Exercising in an immersive 3-dimensional environment with full-field visual simulation should also improve spatial orientation and is typically hard to create in a clinical setting (with 2-dimensional screens). Finally, as in any rehabilitation programme we followed the basic principles of exercise: progressive overload, and specificity to every patient's needs and abilities. These principles of exercise, motor learning and vestibular rehabilitation can be accommodated within virtual reality paradigms [9], because they allow for training in diverse environments, flexibility to control incremental increases in visual and auditory load and creating an immersive experience. The potential of clinical translation is enhanced by the portability and low cost of the HMD setup.

Another factor that could facilitate the clinical implementation of VR applications is their cost. Our app was built with simple, free graphics. The walking virtual pedestrians are designed to create visual flow and do not look like the common person in the street. Simulation fidelity has been defined as the degree to which a device can replicate an actual environment, or how "real" the simulation appears and feels [33]. Some suggest that the higher degree of simulation fidelity, the higher will be the degree of transfer of training to daily living [34]. This notion, however, has not been supported with experimental research, and it has been proposed that adding more fidelity, especially in later stages of training, has varying implications for different individuals and may produce minimal gains of transfer [33,34]. A challenge with high fidelity is the high computational cost associated with the complexity of the graphic models, high level of details, and high quality of lighting [34]. In addition, expensive computation of hyper-realistic scenes can significantly reduce the rendering quality of the HMD because of latency and low frame rate [35]. Latency and delays are critical factors that can cause cybersickness [36]. Abstract, simple visuals require less expensive computational load which may allow for smoother rendering of the display such that participants are less likely to experience cybersickness. This feasibility study found minimal cybersickness with the level of symptoms corresponding to those experienced by patients in their normal daily living. We aimed to enhance the perception of immersion and presence in the scene by adding 3-dimensional realistic sounds [37,38]. In a preliminary study with healthy adults (unpublished data) all participants reported an increase in immersion and perception of "presence" when experiencing the subway scene with sounds compared to without. How real should the visuals appear (simulation fidelity) to facilitate transfer to real-life function is an important question for rehabilitation science [34]. If simple virtual pedestrians are good enough to create individualised and context-specific [3,39] assessment and rehabilitation programmes, the potential for outreach and distribution on a large scale could increase tremendously. A direct comparison between training in apps of different graphic design is needed to further support this notion.

Howard et al. highlighted the importance of future optimisation of VR rehabilitation programmes as well as the need for standardised measures to assess the success of these programmes. Following the World Health Organisation International Classification of Functioning, Disability and Health (ICF), we combined participation and activity level outcome measures [40] while trying to minimise the burden on the participating patients and clinicians. Interestingly, most patients did quite well on the functional outcomes to begin with (8FUG and FSST) and so demonstrated a ceiling effect. While several self-reported outcome measures quantify visual dependence in movement and function in busy environments, currently there is not a standardised objective functional outcome that measures this construct. Outcomes such as the Dynamic Gait Index, Functional Gait Analysis and Clinical Test of Sensory Interaction for Balance have been proposed in this population [41]. Because the study setting was a vestibular rehabilitation clinic, and the study's procedures were only a part of the normal daily load of the clinicians, our choice of outcome measures was driven first by feasibility and minimising the burden of the study procedures.

This study established the feasibility of a novel HMD application to train sensory integration of patients with vestibular disorders in a functional context. However, the descriptive study design, lack of control group and lack of specific protocols limit the generalizability of the results. In addition, because the study was not funded, time in VR was limited. The HTC Vive model used in this study allowed the subject to walk for only a few steps in all directions. Currently untethered HMDs have come out that will allow for several metres of walking within the environments. Our app is compatible with different hardware to accommodate these rapidly changing technologies.

In conclusion, HMD training within increasingly complex immersive environments appears to be a promising viable adjunct modality for vestibular rehabilitation. It is important to establish proof of the effectiveness of all new technologies and generate user guidelines before new devices are made available commercially [15]. To test effectiveness, our next step is to run a pilot randomised controlled trial where patients could go through a longer, structured virtual reality programme and their performance will be compared to patients going through a more traditional vestibular rehabilitation without VR.

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ORCID

Anat V. Lubetzky http://orcid.org/0000-0001-5869-025X

Data availability statement

The data the support the findings of this study are openly available in: https://data.mendeley.com/datasets/3w7j974zp7/draft?a=94c07aad-a708-4e87-b981-a5503d6537a3

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