Head Mounted Display Application for Contextual Sensory Integration Training: Design, Implementation, Challenges and Patient Outcomes

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***Abstract*—Patients with vestibular disorders display difficulty with multisensory integration and complain of dizziness and imbalance in busy and complex visual environments. Patients who experience symptoms or a fall within a certain environment are likely to develop fear of that situation. It has been suggested that multisensory integration should be addressed in conditions as close as possible to real-life situations, but these are often challenging to replicate in the clinical setting. Virtual reality (VR) can provide a non-threatening method for patients to practice multisensory integration in a functional context. Advances in technology make Head Mounted Displays (HMDs) accessible and affordable in the clinic. We developed a VR HMD application that allows patients to practice contextual sensory integration (C.S.I) while sitting, standing, turning or stepping within diverse scenes. This application can become an integral part of vestibular rehabilitation. For successful implementation, usability is critical. In this pilot, usability and preliminary outcomes were tested in a mixed-methods descriptive study. Six physical therapists in a Vestibular Rehabilitation Clinic treated 12 patients with peripheral or central vestibular disorders. Therapists viewed the system as a bridge for a functional carry over from the clinic to the outside world. While they reported challenges in operating the technology within the clinical time constraints, they liked the ability to gradually introduce a challenging sensory stimulus and bring reality to the clinic. Several patients dropped out prior to completing training. Nine out of 12 patients who completed training thus far improved their disability score, 9 improved their visual vertigo and 10 improved their balance confidence following training with the app. Recommendation for future research and clinical implementation are discussed.**

Keywords*—*Vestibular Rehabilitation, HMD, Virtual Reality, Sensory Integration, Feasibility

I. Introduction

The adaptive nature of the human nervous system calls for training patients in conditions as close as possible to those commonly encountered during daily activities [1]. Patients with vestibular dysfunction typically complain of dizziness and imbalance in busy and complex visual environments [2]. These patients often avoid environments that provoke their symptoms. Such avoidance, however, deprives the individual of the exposure necessary to promote physical and psychological adaptation. Yardley and Redfern highlighted the need to combine rehabilitation for dizziness and multisensory integration with addressing the psychological needs of the patient [3]. Virtual reality (VR) is defined as the computer-generated simulation of a three-dimensional image [4]. VR can facilitate immersion within a variety of environments [5] and provide tasks that target visual dependence within a functional context [6], [7]. Patients' avoidance of anxiety-producing and/or symptom-provoking environments can be reduced via the use of VR since the patient is exposed to them in a safe manner under the supervision of the therapist, and can leave the environment at any time [5].

VR rehabilitation has been used for many years in vestibular rehabilitation and has been shown to be effective with regards to physical outcomes [8] and for facilitating sensorimotor relearning for balance [1]. Meldrum et al. found that VR rehabilitation was equally effective as traditional rehabilitation in patients with unilateral peripheral vestibular loss, but patients performing virtual reality balance exercises reported more enjoyment and less fatigue after the activity [7]. Likewise, training within a virtual grocery store led to similar functional and self-reported changes as traditional training in a group of patients with vestibular disorders [9]. Pavlou et al. demonstrated improvements in gait, anxiety and depression in patients with peripheral vestibular disorders following training in a virtual crowded street within a projection theatre [10].

The world of VR has developed remarkably over the past few years and will continue to grow and become an integral part of our lives. These days, using VR in a rehabilitative setting to address multisensory integration is becoming increasingly affordable and accessible. Head Mounted Displays (HMDs: goggles that are worn on the head in lieu of a screen and projectors), such as the Oculus Rift and the HTC Vive, can potentially allow for a specific and individualized low-cost program, with minimal space requirements and a high level of immersion. Research regarding clinical application of new HMD's is in its infancy, but the results are promising and exciting. The Oculus Rift has been shown to be useful for assessment [11]–[14] and for pain management [15]. HMDs have been shown to be successful within vestibular rehabilitation as well. Head movement training in sitting while participating in a driving scene via the Oculus Rift was found to be effective for patients with unilateral vestibular hypofunction when combined with a traditional vestibular program [16], with benefits maintained at 1-year follow up [17].

We created a clinical application using the HTC Vive headset to provide a graded method for patients to experience these environments in a functional and non-threatening context. Our Vive application allows for contextual sensory integration (C.S.I) where patients are immersed in safe, increasingly challenging environments. These environments are designed to mimic daily sensory load and related symptoms and emotions (fear and anxiety) that patients may experience in their daily living and are not easily reproducible in traditional rehabilitation. We have developed our application based on feedback from patients regarding their daily participation restrictions and from physical therapists about the conditions they would want to be able to reproduce in the clinical setting.

Although the C.S.I app appears promising, the use of technology in daily practice is often not as successful as expected due to lack of technology acceptance in patients and healthcare professionals [18]. For new technology to be implemented successfully in clinical practice, users should be involved in early stages of development and evaluation of the technology [18], [19]. The International Organization for Standardization(ISO, 9241–11) [20] defined usability of a device as the extent to which the device can be used by specific stakeholders to achieve specific goals with effectiveness, efficiency and satisfaction in a specified context of use. Therefore, the purposes of this study were: 1) Describe the app usability from the physical therapists' and patients' perspective; and 2) Evaluate changes in visual vertigo, self-reported disability and balance confidence following an individualized C.S.I program.

II. System Design

A. System/Hardware

Our platform runs at 120 frames per second with either HTC Vive or Oculus Rift, on a Windows 10 laptop with 8GB RAM, Intel i7-7820HK CPU, Nvidia GTX 1080 Max-Q GPU, and Bose SoundTrue around-ear headphones II. The software was developed in C# with Unity3D 2018.2.0f1(64-bit) (Unity Technologies, San Francisco, California). The system utilizes SteamVR. Oculus Rift and HTC Vive both operate at 90 Hz refresh rate, 110 degrees field of view, and a high-definition video of 1080x1200 resolution for each eye. Three-Dimensional audio rendering is implemented using Wwise middleware and Google Resonance audio plugin.

B. Visual Development

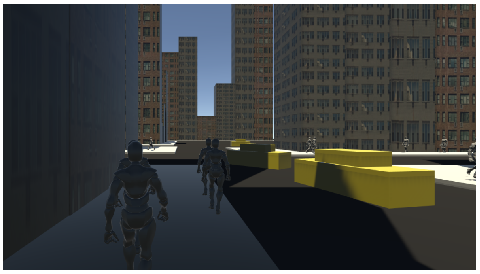
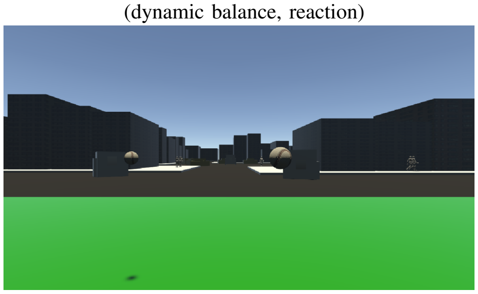
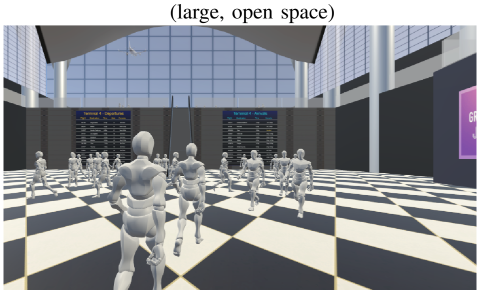
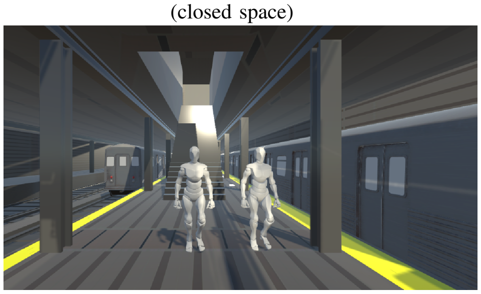
The graphics of the subway station, airport terminal building, and subway trains are modeled in Maya and imported to Unity3D. The rest of the 3D objects are modeled in Unity3D. The subway station model and airport model replicate a real subway station in New York City and a real airport terminal in the US.

The contents in the system are fully controllable by the user interface. The user interface is the entry point of the system, and clinicians can use sliders to switch between scenes, change parameters such as walking directions, amount, speed, number of balls in the park (1-3), and sound levels. They can also use checkboxes to enable/disable scene-specific contents, such as, light transitions, color, texture, trains, or airplanes.

C. Audio Development

The implementation of sound in the system is based on 3D audio, particularly dynamic binaural rendering on headphones. Using the head-tracking data, audio is modulated according to the position of the listener's head. The technology allows for a rich soundscape in all of the directions around the listener. Audio assets used in the system are divided into two main groups: sound objects and ambiances. Sound objects are attached to the visual objects in the scene and their position is changing accordingly. These include the sounds of footsteps, trains, announcements, cars, balls, airplanes, etc. Ambiances are created from original recordings from different locations in New York. These include different background sounds, i.e. sounds of the crowd chatter, distant trains, wind, birds, traffic and general room tone of each of the spaces. All of the sounds used in the system are assigned to three different intensity levels which relate to the increasing complexity of the soundscape and amount of auditory stimuli played at the same time. The lowest level has no sound, the medium level has a minimum number of the sound effects with moderate complexity of background sounds, whereas the highest level creates a bustling auditory environment with a large number of sound cues. Clinicians can adjust the intensity of the audio layer depending on the symptoms and abilities of each patient.

TABLE I
DESCRIPTION OF OUR INTERVENTION SCENES.

Environment	Visual Manipulations	Selected Patient Quotes	Sound Implementation
City (daily function in an increasingly complex environment) 	Walking Direction	"I feel anxious when people come behind me"	• Ambisonics recordings of New York city as a background layer • Cars passing by • Cars Honking • Jackhammer • Ambulance • Police Sirens • City Rumbling Sound (low-frequency noise, mainly caused by traffic) • Foot Steps
	Walking Amount & Speed	"This feels like a mild version of the outside experience" "If I were trying to walk through that, I would not like that"	
	Color	"I was not bothered by the moving objects because they were black and so I could focus on the white"	
	Light	"I feel uneasy in the dark" "I feel uneasiness with the rapid change of light to dark... it's like in the cinema"	
Park (dynamic balance, reaction) 	• The manipulations above • Different directions of balls and multiple balls • Timing of ball appearance is randomized (was constant on first development stage)	"I think that would be a great therapy for making me move my head...If you played with where it goes" "this is engaging!" "If I dodged like that in open space, I would feel dizzy, but I had no problem doing it within the scene!"	• Ambisonics recordings of different parks in New York City as background layer • Bird sounds • Wind • Wind in the trees • Ball woosh • City rumbling
Airport (large, open space) 	• Vary walking amount and speed. Directions include multiple angles. • Materials include colorful signs on the walls and an airplane. • Three locations: center of lower level, by a staircase, mezzanine level.	"I am able to travel but in busy airports I sit in a wheelchair...people 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"	• Ambisonics recordings of spaces similar to airport as background layer • Airport PA announcements • Crowd • Suitcase rolling • Footsteps • Plane flying by
Subway (closed space) 	• Same as airport. • Materials include colorful signs on walls and trains. • Three locations: center of platform, near tracks, mezzanine level.	"I don't feel comfortable standing on the platform, I feel like I will fall over" "I don't take the subway, there are too many people and I am afraid of falling onto the track if someone bumps into me"	• Ambisonics recordings of different subway stations in New York City as background layer • Train passing by • Subway PA Announcements • Footsteps • Crowd • City rumbling

III. Methods

The study took place at the New York Eye and Ear Infirmary of Mount Sinai, Vestibular Rehabilitation Clinic. Six vestibular physical therapists (PTs) recruited patients who were seen at the clinic for vestibular rehabilitation. Included participants were adult males and females (>18 years old) who were clinically diagnosed with a peripheral or central vestibular disorder, including vestibular migraines.

A. Usability Outcomes

PTs completed the System Usability Scale (SUS [21]) after their first usage of the app and monthly thereafter. The SUS quantifies the user's confidence with using the system, ease of use, etc. This questionnaire includes ten items which provide a global view of subjective assessment of a system's usability. Each item is rated on a 5-point scale from 1 (disagree totally) to 5 (agree totally). Five items are positive statements, such as "I think that I would like to use this system frequently" and "I thought the system was easy to use". the other five items are negative, for example, "I found the system unnecessarily complex" and "I think that I would need the support of a technical person to be able to use this system". The overall score ranges from 10 to 100 where higher is better and 68 is acceptable [21]. The PTs also met with the first author monthly for an open-ended discussion including questions regarding advantages, disadvantages and problems with using the app, satisfaction and suggestions for improvements. Patients completed the Short Feedback Questionnaire (SFQ) [22] after the first time they experienced a scene. The SFQ quantifies traits such as immersion, enjoyment, and challenge on a scale of 1 (not at all) to 5 (a lot).

B. Self-Reported Outcomes

All patients completed 3 questionnaires at baseline and following the completion of the VR training: The Dizziness Handicap Inventory (DHI) was designed to identify difficulties that a patient may be experiencing because of his/her dizziness [23]. The Activities-Specific Balance Confidence (ABC) is a subjective measure of confidence in performing various ambulatory activities without falling or feeling 'unsteady' [23]. The Visual Vertigo Analog Scale asks patients to rate the intensity of visual vertigo in 9 situations of visual motions that typically induce dizziness.

C. Procedures

Description of our C.S.I Vive app and how it was guided by patients' stories appears in Table I. Within the app, patients explore a virtual street, airport, park or subway. The PT controls direction, amount and speed of virtual people (5 levels each, starting from an empty space). Level of difficulty can be gradually increased by: visual complexity, task duration (unlimited in the app, clinicians have used 60-300 seconds), patient movement (from static stance to walking within a 4 ft^2, pivot turn, head turns etc.) and scene-specific sounds. No protocol was prescribed but PTs were asked to apply the Kennedy Simulator Sickness Questionnaire [24] at the beginning of every session and repeatedly every few minutes as necessary. They were asked to train patients within the most challenging level that does not induce symptom exacerbation. Should symptoms increase, the patient should take a rest break and the PT should scale back the visual complexity. The PTs used the app for only part of their typical 30-45-minute sessions. In the remaining time they provided patient education, reviewed and progressed the patients' individualized home exercise program.

IV. Results

Over 11 months of study, 26 patients enrolled, and all 6 therapists in the clinic participated. Seven patients dropped out after 1 to 4 sessions due to the following reasons: Anxiety, at physician's request, concern regarding symptoms, stopped coming to therapy, other orthopaedic injuries that happened after enrollment (2 patients). Diagnoses of patients who dropped out included unilateral or bilateral peripheral hypofunction, or vestibular migraine. Here we report results from 12 patients who completed the intervention by the time of this report (7 are still enrolled). Included patients' diagnoses were as follows: 1 Vestibular Migraine, 2 Traumatic Brain Injury, and 9 unilateral peripheral vestibular hypofunction.

A. Therapists Interviews

The following 8 themes came up during 8 meetings conducted over 10 months:

1) Patients are asking for sound to increase the perception of 'real'. Following that meeting we recruited a team from the Music Technology Department to design the auditory aspects of the application (see Audio Development section)
2) Can it be wireless? PTs expressed a concern that the patient may trip over the cable. The Vive wireless adapter came out on November 2018 and we are currently working on adapting the app to a wire-free environment.
3) The PTs asked for timer on the screen. This was not added, and they have been using a stopwatch.
4) The Scene has to retain parameters used. This was modified immediately. Prior to this meeting the app would return to 0 on all parameters once exiting a scene. Keeping the settings as used made the flow between scenes easier.
5) We do not want to use a 'cheat sheet'. Each scene needs to be named rather than numbered (e.g., 'city' rather than '1'). This was modified immediately for the scenes but not for all combinations.
6) The 'up and down button' (changing the height of the scene using keyboard arrows) is great.
7) Barriers to using the app have primarily been related to time. PTs expressed frustration with occasional system failure that required restarting the computer once or more. For example, if a PT blocked the light houses when he/she guarded the patient, a restart was required. Having to go through the research procedures (ID, questionnaire, tracking the data) was also mentioned as a barrier.

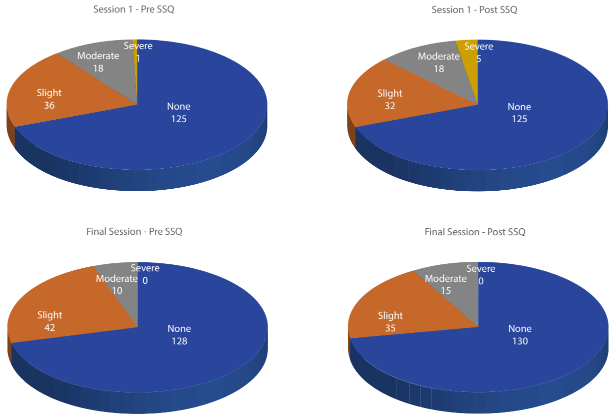


Fig. 1. Number of symptoms (None, Slight, Moderate, Severe) reported by the 12 participants on session 1, pre and post training (top) and on the final intervention session, pre and post training (bottom).

8) Advantages to using the app: “it provides a bridge for a functional carry over”... “controlled introduction of a stimulus...bringing reality to them...”

B. Therapists Usability Data

Average usability scores were 70 when the PTs used the system < 5 times, dropped to 63 at 5-10 times usage and increased to 73 above 10 times. When we introduced a new application that included the environmental sounds, we also replaced the desktop to a new laptop. With the new app usability scores of therapists who have been using the app for several months dropped slightly to 69.4.

C. Intervention Protocol

There were multiple combinations in terms of how PTs chose to use the app with their patients. The most common progressions were in duration of scenes (from 60 seconds up to 5 minutes); the complexity (from minimal to maximal amount and speed) and the task (from sitting to standing supported to free standing, head turns and walking). An example for a representative protocol from 1 patient with peripheral hypofunction who completed 8 session, appears in Table II.

D. Patient Quotes and Short Feedback Questionnaire

Table III shows average SFQ data per scene. Note that we modified the scale by removing the question regarding feedback and success in the task. Patients completed the SFQ upon experiencing a new environment. These scores do not include the auditory changes.

E. Symptoms

Figure 1 demonstrates the results from the 15-item Simulator Sickness Questionnaire. The 12 participants reported the number of symptoms (none, slight, moderate, severe) they experienced on the first and last training session. Overall, symptoms were ’none’ to ’slight’ for most participants on both sessions. Note that 4 out of 5 severe symptoms post Session 1, and 9 out of 15 moderate symptoms post the final session came from an individual patient with a central vestibular disorder who was highly symptomatic regardless of the VR experience.

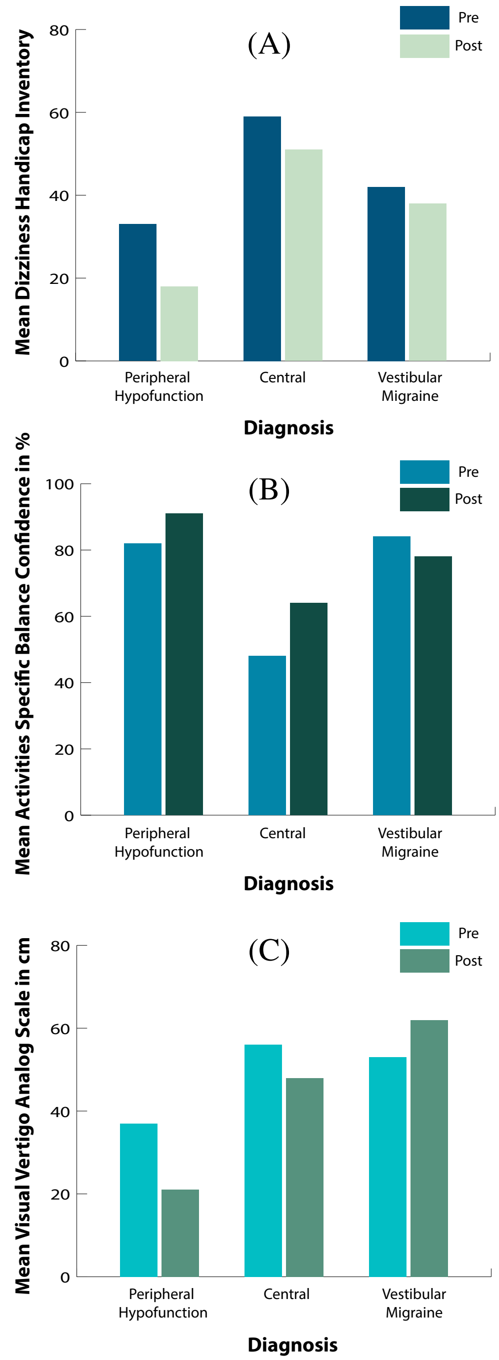


Fig. 2. Changes from baseline to post intervention on: A. Dizziness Handicap Inventory (top); B. Activities Specific Balance Confidence (middle); and C. Visual Vertigo Analog Scale (bottom). Values are presented per diagnosis: Peripheral Hypofunction (9 patients); Central Disorder (2 patients); and Vestibular Migraine (1 patient).

F. Patient Outcomes

Figure 2 shows changes in self-reported outcomes from pre to post intervention according to diagnosis. Wilcoxon signed

TABLE II

A REPRESENTATIVE EXAMPLE FOR PROTOCOL ADMINISTERED IN ONE PATIENT WITH UNILATERAL PERIPHERAL HYPOFUNCTION

	Scenes Performed	*Duration per Scene*	*Visual Load*	*Patient Tasks*
Session 1	City X 2, Subway X 2, Airport X 1	60 seconds	Minimal amount (1) minimal speed (1)	Standing, head turns, walking?
Session 2	City X 2, Subway X 1	120 seconds	Amount level 2, speed level 2, light and dark	Turning around, turning head in all directions, walking
Session 3	City X 2, Park X 1, Airport X 1	180 seconds for city and park, 60 sec for airport	Amount & speed level 3 for city and park; level 4 for airport	Walking around the scene, dodging the ball in the park
Session 4	City X 1, Subway X 1	300 seconds for city, 90 sec for subway	Amount & speed level 4 for city, level 3 for subway	Walking around the scene, head turns, dodging ball
Session 5	City X 1, Airport X 1, Park X 1	240 seconds for city and airport, 180 sec for park	Amount & speed level 4 for all	Walking around the scene. Looking behind her, dodging the ball
Session 6	City X 1, Park X 1	300 seconds	Amount & speed level 4 for all	Looking up while walking around, dodging the ball
Session 7	City X 1, Park X 1	300 seconds	Amount & speed level 4 for all	Same, turning
Session 8	City X 1, Park X 1	300 seconds for park, 180 sec for city	Amount & speed level 4 for all	Same

rank comparison of these scores among patients with peripheral hypofunction (n=9) only showed a significant difference on the DHI (P=0.02, Fig. 2A, mean change 15 points), the ABC (P=0.04, Fig. 2B, mean change 8%), but not on the VVAS (P=0.09, Fig. 2C, mean change 16 cm).

Both patients with central disorders improved on all measures, but the patient with vestibular migraine scored higher (more symptoms) on the VVAS and had minimal gains on the other 2 measures.

V. DISCUSSION

The Contextual Sensory Integration app has been developed together with patients and clinicians to answer an expressed need: a bridge from training in the safe, predictable clinical environment to the sensory experience in the outside world. Off-the-shelf VR programs have been used for many years in vestibular rehabilitation and overall have been shown to be effective for various vestibular disorders [8]. Recent advances in head-mounted display (HMD) technology allow for high level of immersion at low costs and minimal technical requirement [13], [14], [16]. Immersive environments can mimic daily sensory load and induce related symptoms and emotions (fear and anxiety) that patients may experience in their daily lives and are not easily reproducible in traditional rehabilitation. Our long-term goal is to provide a streamlined, individualized, user-friendly intervention platform ready to be tested in clinical trials; leading to improved participation restriction and quality of life following an individualized training in virtual environments.

The system was feasible, and for the most part, easy to operate. Nevertheless, usability scores remained no higher than acceptable throughout an entire year of data collection. Implementation challenges included guarding the patients without blocking the Vive light-houses. In addition, occasional windows updates would require a system restart that will take away from treatment time. The therapists were able to operate the user-interface but still wanted the simplest application possible with no need for calibration. Since no calibration was done, the limits of the virtual environments were not defined, which required constant guarding of the patients to avoid them from bumping into objects in the room. We are currently adapting our application to a wireless setup. This may resolve the aforementioned challenge since walking in the virtual environment will be less constrained.

A. Limitations and Directions for Future Research

The application we developed allows for a highly individualized intervention plan. While this may be desired clinically, it makes a controlled scientific investigation of its effects quite challenging. In the current study, the therapists had complete freedom to use the application for their specific patient in terms of duration, scenes chosen, visual load, task, etc. In a future controlled study, we may need to provide more guidelines, e.g., progress with one parameter at a time and specify criteria for progression. This will help us discern which patients may benefit from this intervention the most. In the current study, patients with peripheral and central vestibular disorders improved, whereas a single patient with vestibular migraine did not improve following training with the app. However, since this was only one patient, these findings should be replicated in a larger study before they can be generalized. Lastly, since this study was not funded, the therapists were limited in the amount of time they could spend in the app during a treatment session. It is possible that treatment effects will be enhanced with longer training sessions inside the application.

In conclusion, the Contextual Sensory Integration app appears to fit well within a vestibular rehabilitation clinic. The patients enjoyed the scenes. Cybersickness was minimal, particularly on the milder scenes. The PTs reported implementation challenges, but overall liked the system and viewed it as a bridge from the clinic to the outside experience. Most of

TABLE III
AVERAGE SHORT FEEDBACK QUESTIONNAIRE (SFQ) [22] SCORES PER SCENE

Scene	Enjoyment	Feeling Inside	In Control	Realistic	Discomfort	Difficulty	Total Score
City	4.27	4.07	4	3.67	1.87	1.6	16
Subway	4.57	4.43	4.14	3.43	2.14	1.71	16.57
Airport	4.17	4.33	4.5	3	1.3	1.17	16
Park	3.75	3.75	4.25	3.25	1.25	1	15

the participating patients improved on self-reported outcomes. Suggestions for improvements included adding auditory cues and transitioning to a wireless system. Future research should employ a more controlled protocol across participants and include a comparison group.

ACKOWLEDGMENT

We thank Laura Lei Rivera, DPT, GCS, Santosh Krishnamoorthy, DPT Joanne Hernandez, DPT, and John Sutera, DPT for their collaboration and incredible contribution to the study.

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