

A virtual reality platform to simulate orientation and mobility training for the visually impaired

Fabiana Sofia Ricci¹, Alain Boldini², Mahya Beheshti^{2,3}, John-Ross Rizzo^{1,2,3,4} and Maurizio Porfiri^{1,2,5*}

¹Department of Biomedical Engineering, New York University Tandon School of Engineering, Six MetroTech Center, Brooklyn, NY, 11201, New York, USA.

²Department of Mechanical and Aerospace Engineering, New York University Tandon School of Engineering, Six MetroTech Center, Brooklyn, NY, 11201, New York, USA.

³Department of Rehabilitation Medicine, New York University Langone Health, 240 East 38th Street, New York, 10016, NY, USA.

⁴Department of Neurology, New York University Langone Health, 240 East 38th Street, New York, 10016, NY, USA.

⁵Center for Urban Science and Progress, New York University Tandon School of Engineering, 370 Jay Street, Brooklyn, NY, 11201, New York, USA.

*Corresponding author(s). E-mail(s): mporfiri@nyu.edu;
Contributing authors: fsr8343@nyu.edu; alain.boldini@nyu.edu;
Mahya.beheshti@nyulangone.org;
JohnRoss.Rizzo@nyulangone.org;

Abstract

Blindness and low vision are an urgent, steadily increasing public health concern. One of the most dramatic consequences of the debilitating conditions that cause visual impairment (VI) is the loss of mobility. Immobility is a grave impediment to quality of life. Orientation and mobility (O&M) training is a profession specific to VI that teaches safe, efficient and

effective travel skills to persons of all ages and in all types of environments. However, the lack of standardized best practices for objective assessment of performance and the exposure of trainees to harm during training are key hurdles for O&M education success. To partially mitigate these drawbacks, we propose a virtual reality platform that can support O&M trainers in the evaluation and refinement of O&M practise, help O&M trainees learn new O&M techniques in a completely safe, yet realistic, environment, and raise awareness for VI in the general public. The proposed platform is tested with a proof-of-concept experiment that evaluates the clinical utility of a custom VI simulation, the immersivity of the virtual reality experience – a crucial attribute for training and educational purposes – and participants’ disability awareness and gained knowledge about the challenges faced by persons with VI in their daily life. The first concept is tested by assessing participants’ performance in virtual reality-based wayfinding tasks while the second and third are tested through a series of dedicated questionnaires.

Keywords: Assistive technology, disability, human-computer interaction, urban accessibility, travel aid

1 Introduction

Visual impairment (VI) presently affects over 2.2 billion people globally and is precipitated by myriad pathologies ([World Health Organization, 2019](#)). The Centers for Disease Control and Prevention in the United States (U.S.) reports that the most common eye diseases and eye disorders include refractive errors, age-related macular degeneration, cataracts, diabetic retinopathy, and glaucoma ([Chou et al, 2013](#)). Recent worldwide estimates indicate that 43.3 million people are blind, 295 million people have moderate and severe visual impairment (MSVI), and 258 million have mild visual impairment ([GBD 2019 Blindness and Vision Impairment Collaborators et al, 2021](#)). This dramatic picture is further exacerbated by a growing population of elder adults who are living longer lives. It is estimated that by 2050, 61 million people will be blind, 474 million will have MSVI, and 360 million will have mild visual impairment ([GBD 2019 Blindness and Vision Impairment Collaborators et al, 2021](#)).

VI severely impacts the quality of life of those who suffer from these debilitating conditions. Persons with VI have lower rates of workforce participation and productivity ([Alma et al, 2011](#)) and higher rates of depression and anxiety ([Demmin DL, 2020](#)). Likewise, VI adversely affects educational opportunities and outcomes ([Marques et al, 2021](#)). In the case of older adults, VI contributes to social isolation, difficulty walking, a higher risk of falls and fractures, and a greater likelihood of early entry into nursing or care homes ([Jones et al, 2010](#)). The reduction of the quality of life is accompanied by large costs for the society, inclusive of healthcare expenses and productivity losses ([Gordois et al, 2012](#)).

VI is an urgent and increasingly important public health concern. Strategies to effectively reduce functional losses are in dire need. These strategies may help persons with VI find and retain employment, resulting in societal reintegration and the reconstruction of a psychological framework that leads to significant productivity gains. For older adults, functional loss mitigation may result in lower risk of falls and improved social inclusion.

Orientation and mobility (O&M) are two critical skills affected by VIs. The functional loss of these skills has significant repercussions on almost every aspect of life (Goldschmidt, 2018). Orientation is defined as the “knowledge of one’s distance and direction relative to things observed or remembered in the surroundings and keeping track of these spatial relationships as they can change during locomotion” (Bruce B. Blasch, 1997). Mobility is defined as “the act of moving through space in a safe and efficient manner” (Everett and Ponder, 1976). As a result of functional losses in these two skills, VI experience difficulties navigating dynamic and unfamiliar areas (Soong et al, 2001).

O&M training is currently offered to prepare persons with VI to move independently in any environment, familiar or unfamiliar. Overall, training in O&M refers to the skills and techniques required for independent and safe mobility (LaGrow and Weessies, 1994). Through O&M training, persons with VI are taught to enhance their mobility performance by maximizing use of residual vision, if applicable, and other senses, such as hearing and touch, with or without travel aids. Techniques are taught to establish a straight line of motion (for example in hallways) and make accurate turns. In this vein, persons with VI can systematically familiarize themselves with a particular environment, while gaining advanced information about an unfamiliar area (location of stairs, level changes, etc.) (LaGrow and Weessies, 1994).

However, O&M training suffers from two impediments that hinder effective, rapid, and safe learning. First, current O&M assessment and rehabilitation techniques are not standardized with regards to best practices. To date, there has not been a systematic review of the effectiveness of the various interventions used by certified O&M specialists; this is due largely to difficulties in establishing common guidelines for performance assessment of existing techniques (Ballemans et al, 2012). Such a deficiency precludes an evidence-based improvement of O&M training. Second, O&M training is not free of risk, whereby persons with VI are exposed to potentially serious harm. In fact, trainees may experience accidental falls, undesired contact with people and objects, or trauma related to indoor or outdoor mobility (Ballemans et al, 2012). Thus, there is a clear need for platforms that can enable a precise assessment of the performance of different techniques, as well as help persons with VI safely learn O&M techniques (Shoureshi et al, 2017).

Virtual reality (VR) holds promise in addressing key limitations of O&M training. Recent efforts have shown that VR applications could improve quality of life, enhance social participation, and bolster life skills, mobility, and cognitive abilities of persons with disabilities, while providing motivating and interesting experiences (Ghali et al, 2012; Abich et al, 2021). Just as VR can

help those who suffer from disability, it can support the simulation of different, even rare, forms of VI to increase awareness in the general public and provide safe training benchmarks for persons with VI (Boldini et al, 2021).

VR provides specific advantages for O&M training. VR offers a controlled environment in which users can perform specific tasks to measure their performance, such as duration or accuracy of movements, or to train certain actions for rehabilitation purposes (Klinger et al, 2010; Sansone et al, 2021). Thus, this environment constitutes an ideal platform for performance assessment of different O&M techniques and interventions (Lahav et al, 2012). Most importantly, VR allows one to avoid the threats associated with performing O&M training in the real world, especially at the initial stages of training (Lahav et al, 2012). By conducting introductory O&M training sessions in VR, persons with VI can learn and familiarize oneself with new techniques and potentially dangerous situations in a completely safe setting, before performing real training sessions (Lahav and Mioduser, 2005).

Here, we propose a VR platform which consists of three environments for training purposes. Within this platform, we created a pathologic simulation of glaucoma, which is a leading cause for the loss of the peripheral field of vision (Lahav and Mioduser, 2005). To evaluate the potential of our VR platform, we conducted a proof-of-concept experiment where healthy participants performed an O&M path in VR with healthy vision or with a simulated VI. Our experiment, tested the clinical utility of a custom VI simulation by assaying how performance of participants with healthy vision decreased in a virtual wayfinding task. In addition, we tested the immersivity of the VR experience by evaluating participants' Sense Of Embodiment (SoE) during the experiment, by correlating their enjoyment and engagement score, measured through dedicated questionnaires. Finally, we explored the educational value of the VR experience through specific questions about disability awareness and knowledge gained in a second series of dedicated questionnaires.

2 Materials and methods

This section is organized in the following manner: we begin with a description of the hardware and software utilized for the implementation of the platform, along with the experimental conditions and general design considerations. We then focus on two aspects that are critical for O&M training: the design of the environment, including visual and auditory landmarks and obstacles, and the tasks that participants perform along the O&M path. Finally, we present the VI simulation in the VR platform and we summarize the specific hypotheses underlying our experiment and the statistics chosen to test them.

The concept of SoE – the sense of being in the virtual environment, owning and controlling a virtual body – is examined in the Supplementary Information. Therein, we also detail the design interventions that were implemented in our VR platform on the basis of SoE, which plays a central role in the development of effective, powerful VR products for training and education.

2.1 Software and device

The interactive experience was designed using Unity, a cross-platform game engine developed by Unity Software Inc. company (doing business as Unity Technologies, based in San Francisco, California, United States) that offers a primary scripting API in C#, as well as drag and drop functionality. The VR platform was built for the VR headset Oculus Quest (Oculus VR, Irvine, California, United States), a standalone headset that uses embedded mobile hardware running an Android-based operating system and supports motion handheld controller accessories known as Oculus Touch.

2.2 Experimental conditions

Our experiment comprised two conditions, performed by participants with healthy vision. Each group of participants performed a series of tasks, which are usually included and tested during an actual O&M session (Lahav et al, 2015). The first group (control condition) consisted of 25 participants with healthy vision who traversed a virtual O&M path. The second group (glaucoma condition) included 25 participants with healthy vision who crossed the virtual O&M path while experiencing high-fidelity simulated glaucoma. Participants in both groups performed the tasks only once.

In both conditions, we utilized our VR platform together with the Oculus headset and Touch controllers. Participants used the Oculus joystick to navigate a virtual environment, and they received vibration feedback each time an obstacle was hit. The joystick vibrated only after the collision occurred, to simulate contact with the obstacle in VR and assist participants in correcting their path. With this feature, we sought to imitate the sensation of touch that, together with hearing, represents a critical source of spatial information for person with VI. The vibration informed participants of collisions with obstacles, to help them correct their path, as colliding with an obstacle would in real life. As such, the joystick was used both as an input device for navigation decisions and as an output device for vibrotactile stimulation.

For each task, we compared the performance of participants with simulated VI (glaucoma condition) against that of participants without the simulated impairment (control condition). We predicted a difference between the performance of the two groups in tasks that involved negotiating obstacles and performing a daily living activity, both of which are known to be difficult for persons suffering with moderate-severe glaucoma (Lahav et al, 2015; Brouwer et al, 2008; Campisi et al, 2021).

2.3 General design

Our VR platform is intended to provide O&M specialists with a technology that can be used to teach persons with VI how to move from one place to another in an informed, efficient, and safe manner, as well as to enhance their involvement in an immersive virtual experience. In this vein, we sought to

create an interactive simulation to provide users with opportunities to engage in realistic environments.

Toward exposing trainees to a variety of environmental situations, we implemented an O&M path in both indoor and outdoor environments. These environments were designed to constitute a test-bed for the most frequent mobility difficulties reported by persons with VI, especially when moving alone or in unfamiliar places ([Dowling et al, 2003](#)):

- obstacles (low-laying objects, head-high, and low-hanging objects);
- misalignments along the intended travel path;
- street crossing (inability to distinguish the color of traffic lights and crossing without traffic lights);
- unwanted contact with pedestrians (which can be socially awkward and may pose a threat to safety);
- lighting conditions and adapting to changes in lighting; and
- drop-offs (negotiating steps, curbs, and ramps) and changes in terrain (broken or uneven sidewalks, street, and surfaces).

Specifically, the experiment included three environments: two urban scenarios and the inside of a house. The rationale for the design of two urban scenarios and one inside of the house is based on the activities and tasks that usually characterize an O&M training. Specifically, the choice to build two urban scenarios was made to evaluate participants behavior in different environments pre- and post-side of a bus trip and with different tasks. The inside of the house was used to test participants' behavior in an indoor environment while performing a daily-life activity. Also, the whole organization of the platform was aimed at realistically recreating an O&M session that did not exceed a maximum duration of 30 minutes, thereby avoiding any potential discomfort associated with prolonged use of VR ([Oculus Safety Center, 2021](#)).

The experiment was preceded by a tutorial, set in an urban scenario similar to that of the experimental scenes to allow users to acclimate to the virtual space and experience. The tutorial scene enabled users to familiarize oneself with the device and controls by means of a series of written and audio instructions and short activities. After a brief written introduction about the purpose of our platform, the actual tutorial began. At first, users were asked to turn 360 degrees to look at the surrounding environment. In order for users to learn how to move around, they were asked to reach a target using the controller ([Fig. 1a](#)). Toward training participants in using the controllers to interact with virtual objects, they were instructed to collect three coins and put them into a basket ([Fig. 1b](#)). Finally, the users were encouraged to listen carefully to the audio-guides that were provided during the experience, to avoid hitting obstacles, and to perform tasks as fast as possible.



Fig. 1: Example of written instructions and activities included in the tutorial scene: (a) walking towards a red target and (b) collecting coins.

2.4 Environmental design: visual and auditory landmarks and cues

For the design of the three virtual environments, we took inspiration from the O&M training literature (Goldschmidt, 2018) (see Video S2 in the Supplemental Material). We built scenarios that were realistic and included obstacles that persons with VI may encounter during both indoor and outdoor mobility. To this end, the indoor scenario included common obstacles and hazards that may be present in the inside of a house, such as low-lying tables and furniture, cabinets, chairs, pots for plants, floor lamps, toys, and narrow pathways between rooms (Fig. 2a). Similarly, typical city obstacles, like steps, ramps, construction sites, vending stalls, parks, and other pedestrians were placed in the outdoor scenario (Fig. 2b). All the city furniture was arranged to create misalignment in the path, a significant threat for persons with VI. We also simulated a bus ride from the first to the second urban environment, to incorporate in the VR platform some of the challenges that are faced by persons with VI during commuting, specifically when utilizing public transportation (Fig. 3). To the authors' knowledge, this is the first time this activity has been simulated.

Virtual environments included both visual and auditory landmarks and cues, that is, permanent or transient elements that provided specific information to users about their own location in the environment (Everett and Ponder, 1976). These landmarks could be used by persons with VI to establish and maintain directional orientation, provide a reference point for navigation goals, establish and maintain distance relationships between themselves and objects or between environmental features, locate specific destinations, orient or reorient themselves to an area, and obtain information about an area (Everett and Ponder, 1976).

In the first scenario, we made considerable use of street signs for providing information about the correct direction to follow or for indicating sites difficult



Fig. 2: Examples of obstacles included in the indoor and outdoor scenarios: (a) disorganized bedroom and (b) construction site.



Fig. 3: Implementation of a bus stop to simulate a bus ride.

to identify, such as construction sites and the park entrances/exits. Spatial and situational information was based on iconic and spatialized visual landmarks or sound cues, which helped users identify their location in the scene and the presence of people around them. For instance, we added animated road workers in the proximity of the construction site or a fountain and other animated characters in the park (Fig. 4a-b). When users reached the park, they heard the sound of water from a fountain and a conversation between two girls sitting on a bench. Additional landmarks were placed in the second scenario. Specifically, we utilized a restaurant with outdoor tables and seating and a gas station in the proximity of a sidewalk, which could be useful to identify the presence of a road (Fig. 4c-d). The restaurant was provided with an audio source playing general noise coming from people talking and eating, which could be heard by users when in close proximity. When users reached the sidewalk, they saw other pedestrians and heard the noise of street sounds that could be helpful to indicate the presence of the crosswalk.

In general, sound cues were specialized and matched the user's egocentric heading. For example, if a user walked close to the bench located on their right side where the two girls sat, the sound of their voices would be heard in the

user's right ear. If the user was facing the sidewalk, the street sound would be heard in both ears. Finally, global environmental sounds were implemented to create an even more motivating and immersive experience, while providing additional auditory cues about the environment inclusive of those related to distraction (Wiener et al, 1997).

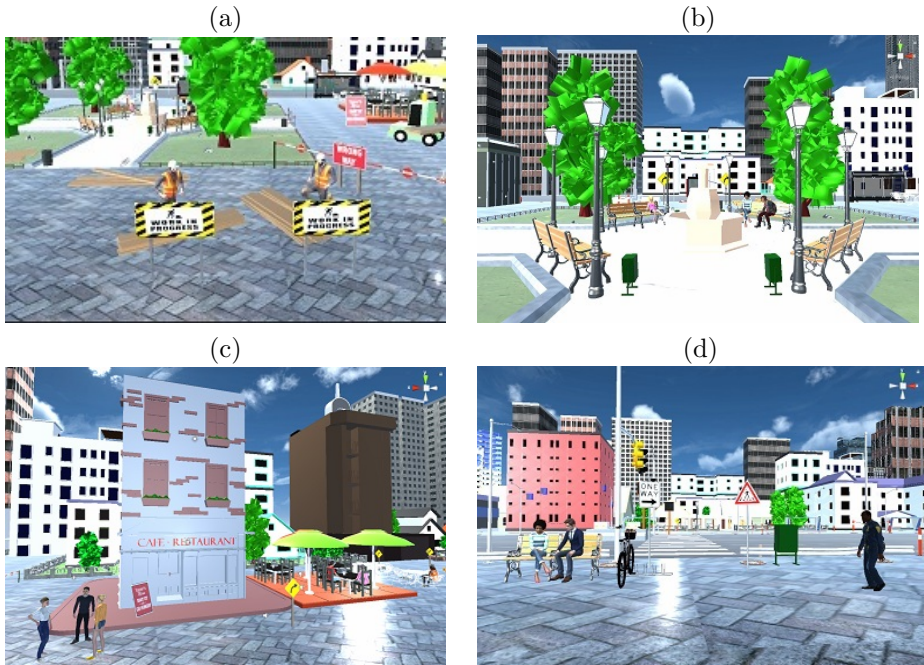


Fig. 4: Example of landmarks included in the two scenes: (a) road workers, (b) park with animated characters, (c) restaurant, and (d) sidewalk.

2.5 Glaucoma simulation

We proposed a multidimensional VI simulation of glaucoma (see Video S3 in the Supplemental Material). We focused on this disease since it is a leading cause of blindness in the U.S. (Congdon et al, 2004). According to the Glaucoma Research Foundation, about three million people in the U.S. have glaucoma, although many of them may not even know it (Stein et al, 2021).

Glaucoma damages the eye's optic nerve and results in vision loss and blindness. It occurs when the normal fluid pressure inside the eye slowly rises (Congdon et al, 2004). Even though the progression of the disease may be slowed with medication and surgery, glaucoma cannot be cured (Congdon et al, 2004). Vision loss due to glaucoma has traditionally been described as loss of peripheral vision, that is, loss of vision at the outer edges (Stamper et al,

1970). However, glaucoma may involve deterioration in the quality of vision in addition to narrowing of the visual field (Hawkins et al, 2003). Several studies demonstrate that deterioration of contrast sensitivity and color discrimination can occur early in the disease process (Hawkins et al, 2003). The most common symptoms reported by patients, including those with early or moderate glaucoma, are dimness or cloudiness, blurriness, difficulty seeing objects to one or both sides, as if looking through dirty glasses, and trouble differentiating boundaries and colors (Hu et al, 2014).

To reproduce the effects on light and vision due to glaucoma, we made use of Unity’s graphics features that allowed for optimizing the graphic rendering of our application. Among all the available graphics features, we chose the Universal Render Pipeline (URP), which included an integrated implementation of post-processing effects. These graphic features also allowed for creating an optimized graphic with capabilities and performance characteristics suitable for our application. URP uses the Volume framework for post-processing effects; the *Mode* property that defines whether the Volume is Global or Local. In our case, we set the *Mode* to Global, such that the Volume affected the Camera everywhere in the Scene.

We utilized the following post-processing effects available in the URP:

- *Bloom* affects the overall lighting of the scene, such that it could be used to reproduce dimness and glare. By adjusting the properties intensity, scatter, and tint we could set the strength and radius of the Bloom and select color for this effect to tint to, in the way we deemed most appropriate. Also, we made use of an additional Bloom effect feature, *Lens Dirt*, which could be implemented to apply a full-screen layer of smudges or dust that simulated the reported difficulty seeing objects from one or both sides, as if looking through dirty glasses.
- *Color Adjustments* tweaks the overall tone, brightness, and contrast of the final rendered image. By adjusting the properties contrast, hue shift, and saturation, we could shrink the tonal range, shift the hue to shades of gray, and lower the intensity of all colors to recreate deterioration of contrast sensitivity and trouble differentiating colors realistically.
- *Depth of Field* applies a depth of field effect, which simulated the focus properties of a camera lens. We chose the Bokeh mode for the depth of field since it closely imitates the effect of a real-life camera. In photography, “Bokeh” is the quality of the blur produced in out-of-focus parts of an image and can be used to recreate blurriness in the simulation. By setting the properties Focal Distance, Focal Length, and Aperture, we could increase the blur intensity and the area interested by this effect as desired.
- *Lens Distortion* distorts the final rendered picture to simulate the shape of a real-world camera lens. We used this effect to simulate difficulty seeing objects to one or both sides and the trouble differentiating boundaries. By setting the properties Intensity, X Multiplier, and Y Multiplier, we could control the overall strength of the distortion effect and its intensity along different directions in the visual field.

Finally, to reproduce the peripheral vision loss, we referred to the National Eye Institute VR “See What I See” app, which allows one to experience vision loss from common eye diseases, inclusive of glaucoma (Figg, 2021). Accordingly, we created an image that we used as a filter in front of the camera, representing the eyes of the user. To increase the intensity of this effect, we added another post-processing layer available in the URP, *Vignette*, in which photography denotes the effect used for darkening and/or desaturating an image towards the edges. By adjusting the properties center, intensity, and smoothness, we set center point, strength, and smoothness of the vignette borders. An example of our final result is shown in Fig. 5. The fine tuning of the glaucoma simulation to reach realistic results was performed with the help of a certified O&M specialist and low vision therapist.



Fig. 5: Example of glaucoma implementation.

2.6 Tasks and performance metrics

The O&M virtual navigation was organized in different wayfinding tasks, addressing multiple O&M skills that persons with VI are expected to gain during O&M training. This architecture also allowed us to understand which skills were affected by the VI and the extent of the performance deterioration. Each task was introduced to the participant through auditory instructions, which could be repeated during the task by pressing a button of the joystick. In the following, we detail each task in both scenes.

The first scene was divided into the following tasks:

- a. *Outdoor mobility and obstacle avoidance.* At the beginning, participants were placed near a construction site and instructed to reach the bus station on the other side of the road as safely as possible, while avoiding collisions. To do this, they had to cross a park populated by different obstacles (bin, streetlamps, branches, fences, and trees) and animated characters. Mobility skills were assessed through the time required to complete the trip and the number of mobility incidents, which included contact with any object or character.

- b. *Transportation system use.* Once participants reached the bus station, they had to pay attention to the coming bus, and walk on a circular spot that would then appear on the sidewalk, approximating the stopping location of the bus and therefore the bus door. Users had to reach the spot in order to proceed to the second scene. We did not simulate the entrance/exit from the bus because getting on and off requires the development of a complex eye foot coordination which cannot be taught or tested in VR. This specific skill could be effectively acquired or assessed through the implementation of a more sophisticated bus transportation system in augmented/mixed reality. The performance of the user was assessed in terms of time spend identifying the bus and reaching the spot for completing the task.

The second scene was divided into the following tasks:

- c. *Outdoor mobility and obstacle avoidance.* Participants were asked to walk in a cityscape strewn with urban obstacles and other pedestrians, to reach a pedestrian crossing. Mobility performance was assessed through the total trip time (seconds required to walk through the environment to reach the street crossing) and the number of mobility incidents.
- d. *Street crossing.* Paying attention to the traffic lights and traffic direction, participants had to cross the street to reach the house on the other side. The ability to cross streets was tested by considering the time required to cross the road together with participants' ability to appropriately cross the street (with the light/ against or not).
- e. *"Treasure hunt".* After crossing the street and entering the yard of the house, participants searched for a hidden key that would allow them to open the door and enter the house. The performance of the subject was assessed in terms of time spent finding the key and opening the door.
- f. *Indoor mobility and daily-life activity.* Participants were tasked to reach the bedroom in the house. Mobility skills inside the house were assessed by the number of mobility incidents (contact with any object) and time required to reach the bedroom. Once in the bedroom, the subject was required to clean up the room by putting socks and towel rolls, scattered all over the room, into a laundry basket, in the shortest time possible. Other object types were present in the scene as confounders, to test whether the subject was able to distinguish those that actually had to be returned to correctly fulfill the task. This activity, which concluded the experiment, was also timed.

We recognize that other metrics could be utilized to quantify the performance in O&M training, such as task completion accuracy and efficiency or error rates (Paliokas et al, 2020; Zhao et al, 2019). However, in this first proof-of-concept study, we utilized only time to completion and number of collisions, which are the most intuitive and easy to acquire during the tests.

The maximum time for completing the whole experiment was 30 minutes to avoid any potential discomfort associated with prolonged use of VR (Oculus Safety Center, 2021). The specific time allocated to each task was chosen based on pilot tests. More specifically, participants were not granted more than two

minutes to carry out simple tasks, such as reaching and crossing the park, taking the bus in the first scene, opening the front door of the house and reaching the bedroom in the second scene. They were also not given more than five minutes to carry out more complex tasks such as reaching and crossing the crosswalk and finding the key in the second scene. Finally, they were not allowed more than ten minutes to carry out the daily-life activity implemented in the bedroom scene. If a participant was unable to complete one or more tasks in the allocated time, they were scored the maximum allowable time associated with that task.

2.7 Participants

A total of 50 healthy participants with a mean age of 22.48 years (standard deviation 4.114 years) participated in the study. Of these, 24 were male, 25 were female, and one was non-binary. In order to avoid any discomfort due to the VR device, we integrated strict exclusion criteria: people with significant cognitive dysfunction, previous neurological illness or psychiatric, heart condition or other serious medical condition, significant mobility restrictions, seizures, interfering medical devices, and pregnant or elderly individuals. The 50 healthy participants were recruited from the New York University (NYU) Tandon School of Engineering. Half of these participants performed tasks with and without the high-fidelity simulated glaucoma. All participants provided written informed consent in accordance with procedures approved by the Institutional Review Board (IRB) at NYU Langone Health (IRB i21-00925). The performance assessments of healthy participants were carried out at the NYU's Center Urban Science and Progress (CUSP, 370 Jay St, Room 1203, Brooklyn, NY, 11201).

2.8 Questionnaire

The questionnaire we designed focused on evaluating the effectiveness of our platform in promoting disability awareness and knowledge, as well as enhancing a higher-level VR experience immersivity, which may lead to a stronger sense of embodiment, presence, and engagement. In the debriefing post-experiment, participants were also asked to report any VR sickness effect. In the control group, 18 reported little dizziness, 2 reported loss of balance, and 1 reported nausea. In the glaucoma group, 10 reported dizziness, 4 reported nausea, 2 reported headache, 1 reported disorientation, and 1 reported eye strain.

The notions of presence and embodiment were assessed in the sections of the questionnaire pertaining to game experience and presence, which were completed by the participants in the glaucoma group after the experiment. The questionnaire consisted of 16 statements that addressed participants' game experience, that is, how the subject felt while and after navigating in VR, and an additional 15 questions that assessed their subjective feeling in terms of sense of self-location, sense of agency, and sense of body ownership. The total

scores assigned to the first and second sets of responses were used to quantify users' enjoyment and engagement, respectively. Enjoyment was defined as the pleasure a user experienced because of being exposed to a particularly interactive experience, while engagement was the extent to which a user felt immersed in the virtual environment by investing time, effort, and attention in the virtual environment.

For the first set of statements on enjoyment, the participant chose a level of agreement using a five-point scale (not at all, slightly, moderately, fairly, extremely). Responses were associated with a score, ranging from 1 to 5, increasing with the level of agreement (Table 1). For the second set of questions on engagement, participants were asked to characterize their experience in the environment by marking an "X" in the appropriate box of a 7-point scale, in accordance with the question content and descriptive labels (Table 2). Participants were also prompted to consider the entire scale when marking their responses, to answer the questions independently in the order that they appeared, and to not skip questions or return to a previous question to change their answer.

Variable	Statement to be graded	Mark
Enjoyment	I was interested in the tasks	1-5
	I felt successful	1-5
	I felt bored	1-5
	I found it impressive	1-5
	I forgot everything around me	1-5
	I felt frustrated	1-5
	I found it tiresome	1-5
	I felt irritable	1-5
	I felt skillful	1-5
	I felt completely absorbed	1-5
	I felt content	1-5
	I felt challenged	1-5
	I had to put a lot of effort into it	1-5
	I felt good	1-5
	I felt exhausted	1-5
	I felt weary	1-5

Table 1: Statements used to quantify users' enjoyment.

Participants in the glaucoma group were also asked to assess their awareness of VIs, through seven specific questions in the education section of the questionnaire. Participants could answer yes or no to the first two questions and they could choose a level of agreement using a five-point scale (not at all, slightly, moderately, fairly, and extremely). Responses to the last five questions were mapped to a score, ranging from 1 to 5, increasing with the level of agreement (Table 3).

Variable	Question to be graded	Mark
Engagement	How involved were you in the virtual environment experience?	1-7
	How much did your experiences in the virtual environment seem consistent with your real-world experiences?	1-7
	Please rate your sense of being in the virtual space, on the following scale from 1 to 7	1-7
	To what extent were there times during the experience when the office space was the reality for you?	1-7
	How natural did your interactions with the environment seem?	1-7
	How natural was the mechanism which controlled movement through the environment?	1-7
	How compelling was your sense of moving around inside the virtual environment?	1-7
	How responsive was the environment to actions that you initiated (or performed)?	1-7
	Were you able to anticipate what would happen next in response to the actions that you performed?	1-7
	How much delay did you experience between your actions and expected outcomes?	1-7
	How compelling was your sense of objects moving through space?	1-7
	How much were you able to control the virtual hands?	1-7
	How much did you feel that the virtual hands were your hands?	1-7
	How much did the control devices interfere with the performance of assigned tasks or with other activities?	1-7
	How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?	1-7

Table 2: Questions used to quantify users' engagement.

2.9 Hypotheses and statistical analysis

We tested the following hypotheses:

- H1. Participants with simulated glaucoma take longer to complete tasks than those without simulated glaucoma. This difference is higher for those tasks that are severely affected by glaucoma symptoms, such as performing a daily living activity.
- H2. Participants with simulated glaucoma have more mobility incidents, such as collisions and bumps, in comparison with participants who perform the experiment without simulated glaucoma.
- H3. The percentage of participants showing an unsafe street crossing behavior (crossing with the red light) is higher in those who perform the experiment with simulated glaucoma than those without.
- H4. Participants' enjoyment and engagement scores are positively related.
- H5. Participants' performance is independent of their engagement score.

Hypotheses H1-H3 were tested in terms of the performance of all the users in the experiment. We expected our high-fidelity simulation of glaucoma to affect a variety of metrics, namely, the time to complete tasks, the number of mobility incidents, and the number of unsafe street crossing. We predicted

Variable	Question to be graded	Mark
Awareness	Have you ever heard about visual impairments before?	Yes or No
	Do you believe you have learned anything more about this issue from your participation to this experiment?	Yes or No
	How much were you aware of visual impairments and their consequence on people who suffer from them before your participation to this experiment?	1-5
	In your opinion, how much important is the issue of visual impairments in America today?	1-5
	How useful was this VR experiment in experiencing some of the most common mobility problems encountered by visually impaired in their daily life?	1-5
	How helpful was this VR experiment in understanding what is like to live with vision loss from common eye diseases?	1-5
	Do you think that a VR experience like this could represent a valid and immersive way for educating people about visual impairments?	1-5

Table 3: Questions used to quantify users' awareness of VIs and the educational value of our VR experience.

that participants with simulated glaucoma would take more time to perform tasks than the control group, as glaucoma would severely affect navigation performance. Similarly, the loss of peripheral vision simulated by glaucoma should precipitate an increase in the number of collisions with obstacles along the path. The inability to precisely distinguish colors, as well as blurriness and peripheral vision loss, should also cause an increase in unsafe street crossings (against the red light).

Hypotheses H4-H5 were examined through the questionnaires that participants performing the experiments with simulated glaucoma compiled at the end of the experience. We anticipated an association between enjoyment (the pleasure a user feels because of being exposed to a particularly interactive experience) and engagement (extent to which a user feels immersed in the virtual environment), similar to several previous studies on serious games (Xie et al, 2008; Mouatt et al, 2020; Lin and Peng, 2015). If present, such an association could support future design interventions in the VR platform to enhance enjoyment, and directly benefit engagement. On the contrary, we did not anticipate an association between participants' performance, such as the total time to complete the experiment and the total number of mobility incidents, and their engagement score. If present, such an association would lower the potential of the VR for O&M training, making it viable only for top performers, who are likely those less in need of O&M training.

For all tests, we used a level of significance of 0.05. To test hypotheses H1, we utilized a series of two-tails *t*-test for each of the tasks (Judd et al, 2017). We performed an analogous test for H2, this time over the entire number of mobility incidents during the experiment. For hypothesis H3, which involved a Boolean variable, we compared the percentage of participants showing unsafe street crossing behavior in the two conditions. We utilized the Fisher's exact

test to determine if there was an association between an unsafe street crossing and performing the experiment with the simulated glaucoma. With respect to the questionnaires, we performed a Kolmogorov-Smirnov test to verify normality of enjoyment and engagement scores, as well as of the total time to complete the experiment and total number of mobility incidents. Then, we performed a correlation analysis by computing the Pearson's correlation coefficient (Judd et al, 2017) between: i) enjoyment and engagement scores, ii) engagement score and total time to complete the experiment, and iii) engagement score and total number of mobility incidents. These metrics allowed us to measure the linear dependence between each pair of variables.

3 Results

First, we report results of the comparison between the performance of the two groups in our experiment, with and without simulated glaucoma, in terms of time taken to complete each task, total number of collisions, and street crossing behavior. We then examine the relationship between users' enjoyment and engagement scores based on questionnaire evaluation. Finally, we investigate whether engagement score is associated with the total time to complete the experiment and total number of mobility incidents.

3.1 Performance comparison between groups

By comparing tasks completion time between the control and glaucoma groups, we confirmed hypothesis H1 that simulated glaucoma negatively impacted participants' performance in both outdoor and indoor scenes, for at least some of the tasks. We observed that participants in the glaucoma group showed significant differences compared with controls for the following activities (Fig. 6): reaching the park ($t_{48} = 3.587$, $p < 0.001$), crossing the road ($t_{48} = 3.964$, $p < 0.001$), and performing a daily living activity ($t_{48} = 7.237$, $p < 0.001$).

Although we failed to attain statistical significance for the activity of crossing the park and reaching the house, we observed a negative trend in the group with glaucoma ($t_{48} = 1.772$, $p = 0.083$ and $t_{48} = 1.752$, $p = 0.086$, respectively). On the contrary, simulated glaucoma did not have a significant effect on the time to complete the following activities (Fig. 7): taking the bus ($t_{48} = -0.271$, $p = 0.787$); reaching the crosswalks ($t_{48} = 0.169$, $p = 0.865$); searching for the key ($t_{48} = -0.062$, $p = 0.951$), and opening the front door ($t_{48} = 0.973$, $p = 0.335$), and reaching the bedroom ($t_{48} = 0.617$ and $p = 0.540$).

By considering the total number of collisions in the entire path, we found that the number of mobility incidents was significantly higher in the glaucoma group compared with the control group ($t_{48} = 4.385$, $p < 0.001$; Fig. 8), in accordance with hypothesis H2.

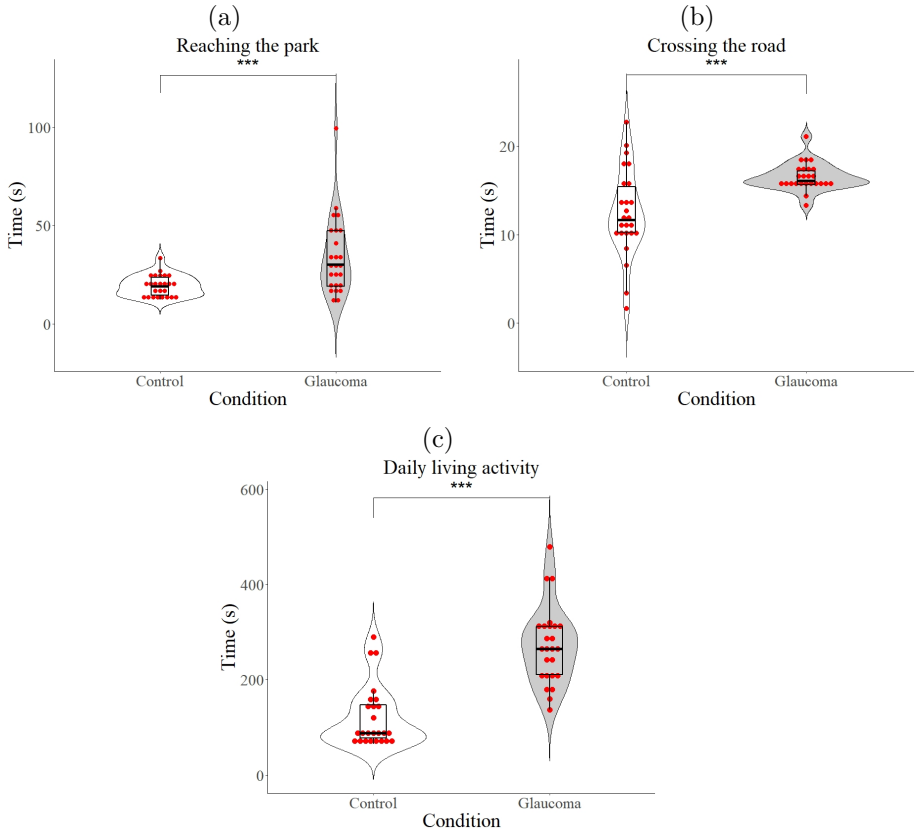
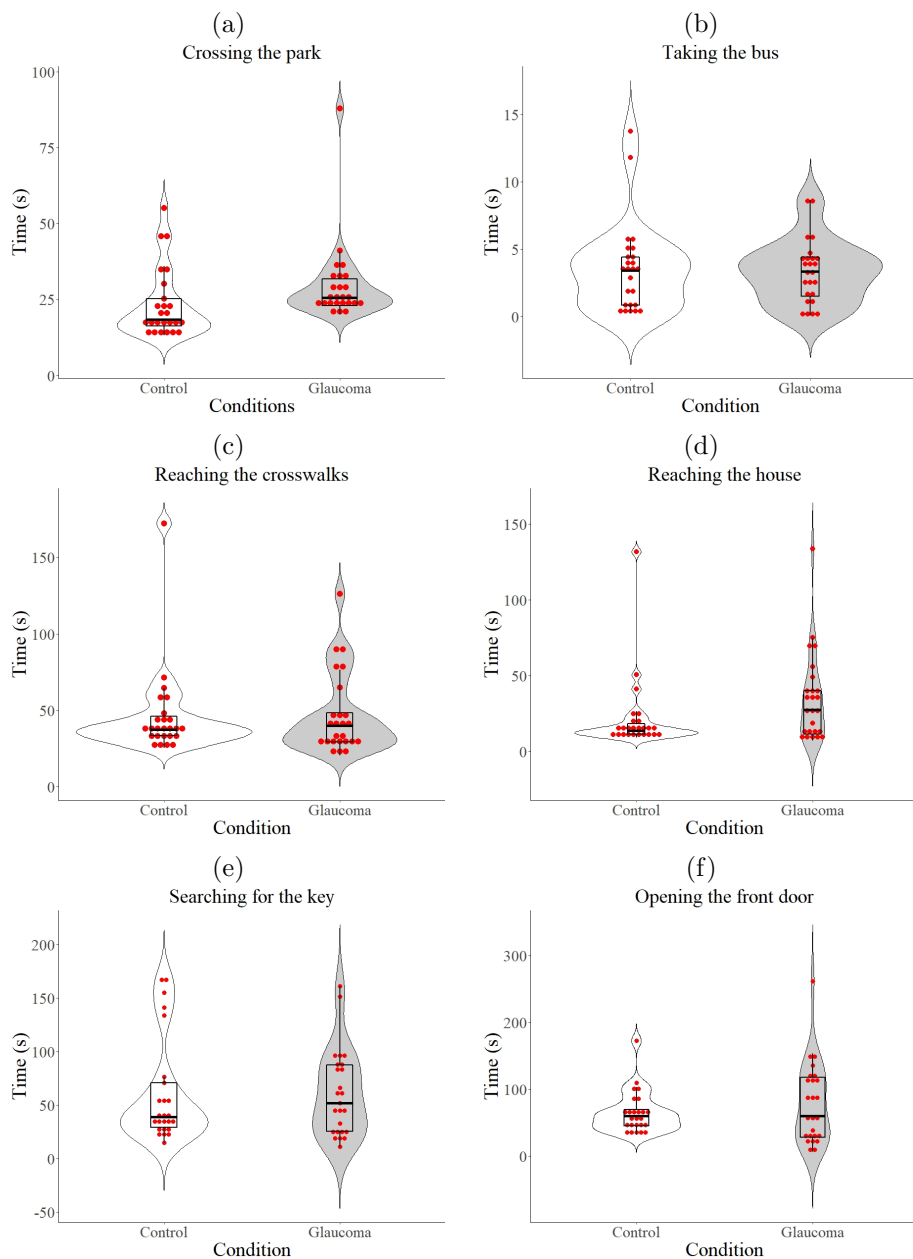


Fig. 6: Effect of the simulated glaucoma on the time taken to complete the following activities: (a) reaching the park, (b) crossing the road, and (c) daily living activity. The area enclosed by black edges inside each violin plot represents the corresponding box plot. The bold black band inside each box details the median, and the bottom and top of the box identify the first and third quartiles, respectively. The colored area of a violin plot corresponds to the empirical probability density of the data. The symbol * * * indicates significant difference with $p < 0.001$ from t -test comparison of conditions.



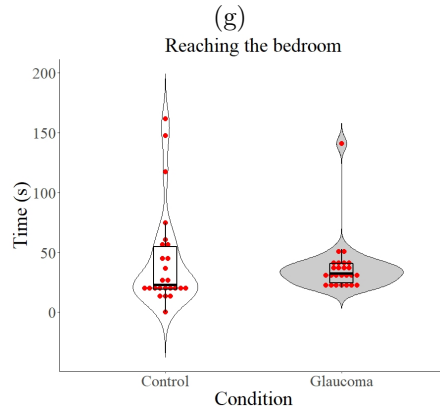


Fig. 7: Effect of the simulated glaucoma on time taken to complete the following tasks: (a) crossing the park, (b) taking the bus, (c) reaching the crosswalks, (d) reaching the house, (e) searching for the key, (f) opening the front door, and (g) reaching the bedroom. The area enclosed by black edges inside each violin plot represents the corresponding box plot. The bold black band inside each box details the median, and the bottom and top of the box identify the first and third quartiles, respectively. The colored area of a violin plot corresponds to the probability density of the data.

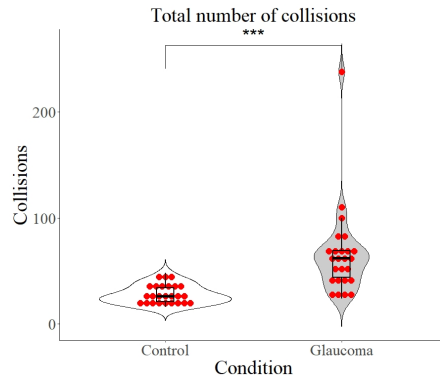


Fig. 8: Effect of the simulated glaucoma on the total number of collisions. The area enclosed by black edges inside each violin plot represents the corresponding box plot. The black bold band inside each box details the median, and the bottom and top of the box identify the first and third quartiles, respectively. The colored area of a violin plot corresponds to the probability density of the data. The symbol * * * indicates significant difference with $p < 0.001$ from t -test comparison of conditions.

Finally, we observed how simulated glaucoma affected participants' street crossing decision at a pedestrian crossing regulated by a traffic light. In particular, we compared the number of participants who crossed the street safely (that is, they started crossing the street only with the white light for pedestrians and red light for cars) between the control and the glaucoma group. We found that only two out of twenty-five participants in the control group crossed inappropriately, resulting in an unsafe pedestrian behavior. On the contrary, eighteen out of twenty-five participants in the glaucoma group crossed the street with the red light (Fig. 9). In agreement with hypothesis H3, we found that there was a significant relationship between the two categorical variables, that is, unsafe street crossing behavior and performing the experiment with the simulated glaucoma (two-sided Fisher's exact test with $p < 0.001$).

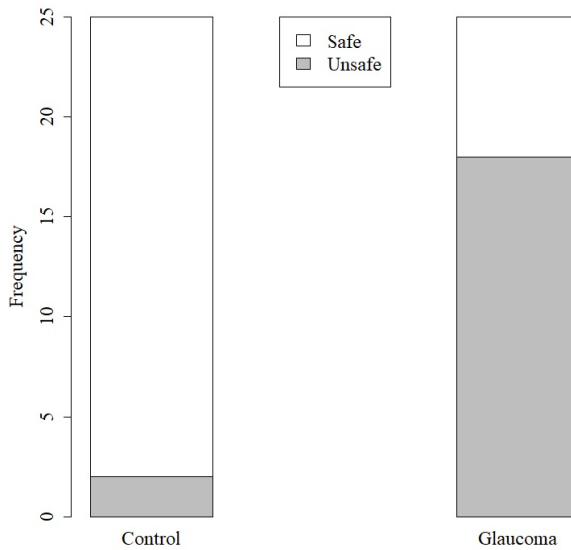


Fig. 9: Effect of the simulated glaucoma on pedestrian street crossing behavior in both groups.

3.2 Analysis of enjoyment, engagement, and disability awareness

The Kolmogorov-Smirnov test confirmed that enjoyment and engagement scores ($D = 0.160$, $p = 0.488$, and $D = 0.119$, $p = 0.826$, respectively), total time spent in VR, and total number of collisions ($D = 0.107$, $p = 0.903$, and $D = 0.129$, $p = 0.751$, respectively) were all normally distributed. By first considering the relationship between enjoyment and engagement scores, we

confirmed hypothesis H4 that engagement is associated with the enjoyment ($r = 0.56$, $p = 0.003$; Fig. 10).

By correlating the time taken to complete the experiment and total number of mobility incidents with participants' engagement score, we did not discover an association ($r = -0.161$, $p = 0.440$ and $r = -0.012$, $p = 0.951$, respectively; Fig. 11), in agreement with our expectations under hypothesis H5.

Although not part of our hypotheses, we also performed a descriptive statistical analysis to examine the level of VI awareness. 80% of the participants declared to have heard about VIs before, and 92% of them thought that the issue of VIs is quite or extremely important in America nowadays. 96% of participants indicated to have learnt more about VIs from their participation to our experiment. 88% of the participants confirmed that our VR experiment was helpful in experiencing some of the most common mobility problems encountered by visual impaired in their everyday life. Finally, 84% of the participants considered a VR experience to be a valid and immersive way for educating people about VIs, as well as for understanding what it is like to live with vision loss from a common eye disease, such as glaucoma.

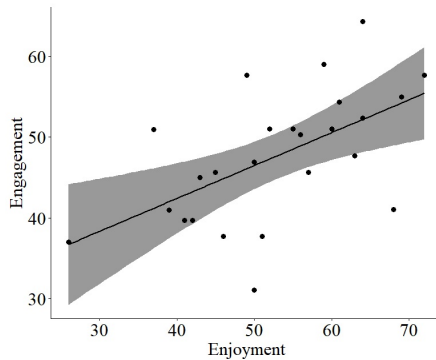


Fig. 10: Scatter plot of enjoyment and engagement scores. Points correspond to individual realizations and the grey area represents the 95% confidence interval of the linear regression.

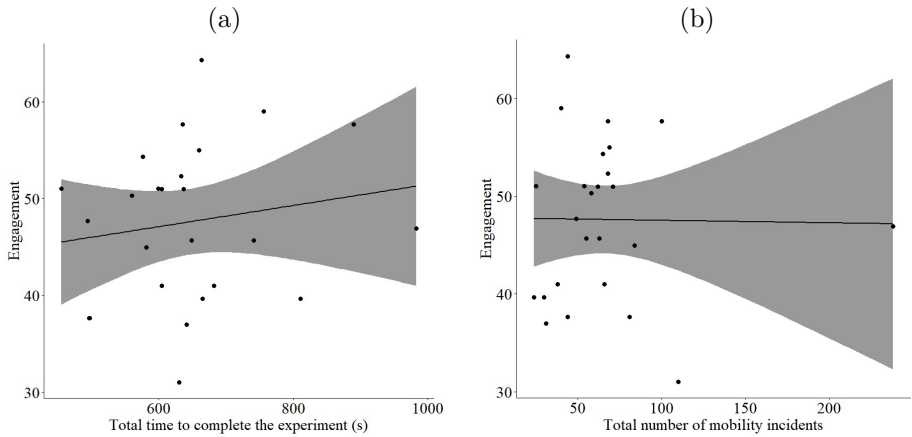


Fig. 11: Scatter plot of engagement and: (a) total time to complete the experiment, (b) total number of mobility incidents. Points correspond to individual realizations and the grey area represents the 95% confidence interval of the linear regression.

4 Discussion

VI precipitates disability with many untoward ramifications. Over the following decades, increased life expectancy and more baby boomers becoming elderly will lead to a rise in the frequency of VI and to greater significant consequences for our society (Allison et al, 2021; Burton et al, 2021; Rokach et al, 2021). Glaucoma is the most frequent cause of irreversible blindness (Congdon et al, 2004; Stein et al, 2021), with far-reaching and debilitating consequences on one's ability to perform many important tasks that compromise mobility and quality of life (Haegele and Zhu, 2021b,a; Kim, 2021). Visual acuity loss and visual field defects caused by pathological high intraocular pressure are the main features of the disease (Congdon et al, 2004). Glaucoma may also involve deterioration in the quality of vision, due to symptoms related to decrements in contrast sensitivity and color discrimination that can occur early in the disease process (Hawkins et al, 2003). Additional vision symptoms that can occur in early or moderate glaucoma are visual dimness or cloudiness, blurriness, difficulty seeing objects to one or both sides, and trouble differentiating boundaries and colors (Hu et al, 2014).

Persons with VI, including those suffering with glaucoma, are generally offered Orientation and Mobility (O&M) training, in which they are taught techniques and skills to move safely and independently within their home and community. Even though O&M training is an established practice, which may reduce mobility limitations and improve social participation and quality of life for persons with VI, it is not free of limitations. In fact, current O&M techniques are not standardized and difficult to systematically evaluate in terms

of effectiveness. Further, O&M training is not free of risks for persons with VI, as sessions often expose trainees to potential harm.

Herein, we proposed a VR platform to simulate O&M training and VI, with a focus on glaucoma. The platform was designed with a three-fold purpose: assisting O&M trainers in developing, evaluating, and refining O&M techniques in a highly controlled environment; providing O&M trainees with a safe platform to learn and become acquainted with new O&M techniques, before applying them in the real world; and educating the general public on the topic of VI and its consequences. The main elements of novelty for our platform include the following:

- *Richness in the interaction*, whereby the virtual environment was designed to constitute a test-bed for the most frequent mobility difficulties reported by persons with VI, such as obstacles, street crossing, unwanted contact with pedestrians, lighting conditions and adapting to changes in lighting, and drop-offs;
- *Realism*, whereby the virtual environment was built to include several key details of indoor (low-lying tables and furniture, cabinets, chairs, pots for plants, floor lamps, toys, and narrow pathways between rooms) and outdoor environments (steps, ramps, working sites, stalls, parks, and other pedestrians) hazards;
- *Simultaneous, cross-modal (visual/audio) presentation of landmarks and cues*, that is, permanent or transient elements that provided specific information to users about their own location.
- *High-fidelity simulation of glaucoma*, through detailed reproduction of the effects on light and vision due to glaucoma, with the Universal Render Pipeline (URP); and
- *Integration with the Oculus headset and Touch controllers*, to offer participants the ability to navigate the virtual environment and receive vibration feedback each time an obstacle was hit (participant-in-the-loop).
- *Wayfinding tasks* that focus on commuting, inclusive of the public transportation use.

We tested the VR platform within a proof-of-concept experiment in which 50 healthy individuals traversed an O&M path, half with a high-fidelity simulated VI (glaucoma group) and half without (control group). We analyzed the role of simulated VI on performance, in terms of time to complete each task, total number of collisions, and street crossing behavior. For each task, we compared the performance of the glaucoma group against that of the control group. We then used a questionnaire for measuring VR engagement and enjoyment of participants in the glaucoma group, two critical aspects for both the training and educational aspects of our VR platform, as well as for assessing the potential of our VR experience to increase disability awareness. We acknowledge that some participants reported discomforts due to VR motion sickness. However, the intensity of the symptoms was very mild and symptoms completely

ceased a few minutes after the participants removed the device. Based on conversations with participants and behavioral observations, we believe that the symptoms reported by participants were mostly due to their lack of experience with the system, as the experiment was their first experience with VR across the board. In fact, with respect to motion sickness, the occurrence and severity of the symptoms is reported to noticeably reduce over repeated sessions (Kennedy et al, 2000). People who are exposed to VR devices become habituated to the device they use routinely, thus becoming less susceptible to VR motion sickness (Kennedy et al, 2000). Moreover, the use of advanced technologies, such as eye tracking in VR, could alleviate motion sickness in users. Eye tracking allows the VR headset to keep track of where the user is looking and adjust the image accordingly, so that they could always be looking at the center of the screen and experience less motion sickness (Bowditch, 2021).

With respect to the performance of the two groups in the experiment, we found that participants in the glaucoma group completed the tasks more slowly than the control group. This evidence is in line with the known challenges that glaucoma poses on mobility (Haegele and Zhu, 2021b,a; Kim, 2021) and it was in accordance with our expectation. Specifically, symptoms such as blurriness, difficulty seeing objects to one or both sides, and trouble differentiating boundaries and colors were expected to hamper the search and correct identification of objects. However, simulated glaucoma affected each task differently. For a first set of tasks (reaching the park, crossing the road, performing the daily living activity, and crossing the park), simulated glaucoma caused a rise in completion time. For a second set of tasks (crossing the park taking the bus, reaching the house, searching for the key, opening the door, and reaching the bedroom), simulated glaucoma led to an increase in completion time.

The difference between these two sets of tasks could be associated with the greater difficulty and duration of those in the first set. Considering activities such as reaching the park, participants could choose different trajectories to reach the target. Healthy vision allows long-range trajectory plans, so control participants were able to apply efficient hazard negotiation strategies, easily estimating the safest and fastest route to reach the goal. Simulated glaucoma interfered with this ability, such that avoiding obstacles that were not in the immediate surroundings and reaching the objective could require re-routing and slowing down, and may cause hesitation. Regarding the road crossing, the difference in the completion time between the two groups could also be attributed to the simulated VI, which prevented participants in the glaucoma group (who were naive to O&M techniques) to make good use of visual landmarks and cues. The failure to identify these visual aids may have caused orientation problems, resulting in the inability to understand where they were and to easily find the location of the pedestrian crosswalks. Overall, these orientation difficulties might have led to more hesitations, longer trajectories, and, ultimately, extended time to complete the road crossing activity.

With respect to the total number of collisions, we confirmed our prediction that participants with simulated glaucoma experienced more collisions than

those in the control group. The larger number of collisions by participants in the glaucoma group was not surprising, since a severe symptom of glaucoma is the loss of peripheral visual field. Specifically, peripheral visual field loss negatively impacted visual search for objects, as peripheral vision provides critical wide-field information about the environment. Similar to the activity of daily living, symptoms such as blurriness, difficulty seeing objects to one or both sides, and trouble differentiating boundaries and colors posed further difficulties to affected participants during obstacle avoidance.

Considering the street crossing behavior, we anticipated that more participants in the glaucoma group than in the control would have crossed the road unsafely. This hypothesis was based on the fact that the diminished colors sensitivity caused by glaucoma would have prevented participants from clearly identifying the color of the traffic light. We found that 72% of the participants in the glaucoma group crossed the road with the red light for pedestrians and white light for cars, resulting in unsafe pedestrian behavior, in agreement with our hypothesis. On the other hand, participants with simulated glaucoma that crossed the road safely likely leveraged audio and visual cues included in our simulation. The audio source used to recreate road noise, together with the implementation of cars regulated by the traffic light, could have helped participants in the glaucoma group to cross the road safely.

In the real world, audio cues are extremely helpful for persons with VI for making crossing decisions (Wu et al, 2018), such that persons with VI are taught to recognize them during O&M training, even though glaucoma prevents persons with VI from clearly distinguishing the color of the traffic light. These results support the effectiveness of simulated VI in deteriorating the performance of participants with healthy vision, such the platform can be utilized by trainers to assess the effectiveness of and refine O&M techniques with healthy participants, reducing the frustration and danger of patients with VI and allowing a larger pool of participants to conduct statistical analyses.

The other two aspects of our platform that we experimentally evaluated were training of persons with VI in O&M techniques and public awareness of the general public. Our first finding was that there was a strong relationship between enjoyment and engagement scores in the glaucoma group. Such a relationship supports the view of enhancing training and educational activities through interactive and entertaining elements that can lead to better learning outcomes for both persons with VI and healthy participants. Increasing the level of identification of persons with VI in the virtual environment may enable them to learn new techniques in a more effective way and to familiarize themselves with novel devices more easily. Likewise, increasing the level of identification of healthy participants with the condition experienced in the virtual environment may contribute in enhancing public awareness about the most common visual diseases and most common mobility problems encountered by visual impaired in everyday life.

The need to measure engagement is critical toward the development of high-quality, specialized VR application for therapeutic interventions (Tao et al,

2021). However, most of the research to date has focused on therapeutic efficacy, with limited attention paid toward game design strategies to enhance engagement (Tao et al, 2021). The link between enjoyment and engagement identified in this study opens the door to targeted design intervention that bolster enjoyment. We also acknowledge the possibility that some of the participants may inadvertently offered an answer to questions on engagement in terms of the perception of their own abilities (Bormann, 2006). This possibility may underlie the lack of a correlations between engagement and both the time taken to complete the O&M path and the number of collision in the glaucoma group. Future work may seek to incorporate other engagement metrics, such as physiological responses (skin conductance response, heart rate, temperature, joint range of motion) (Matthews et al, 2002; Houzangbe et al, 2020; Barak Ventura and Porfiri, 2020; Barak Ventura et al, 2021).

Finally, we evaluated the potential of our VR platform for educational purposes, toward raising awareness regarding the difficulties experienced by persons with VI in their daily life. Poor health awareness of glaucoma and its complications causes a delay in seeking medical care and reduces chances of early intervention and prevention. Therefore, raising public awareness of eye diseases plays a significant role in the early diagnosis and treatment of such condition, toward reducing the overall burden of VI. Overall, we found that the majority of participants in the glaucoma group were aware of visually impairments and of their increasing importance as a public health issue in America nowadays. It is also encouraging that almost all the participants confirmed to have learnt more about VIs from their participation to our experiment and that almost 90% of them consider a VR experience to be a valid and immersive way for educating people about VI. These data offer evidence about the educational potential of our platform, ranging from simply increasing awareness within the general public about VI and its difficulties to favoring early interventions and prevention to reduce the overall burden of VI. A potential approach to ensure a widespread and easy access to our VR platform for educational purposes entails its deployment in low cost, accessible mobile phone-based VR systems, such as Google VR Cardboard.

Beyond the partial assessment of enjoyment through a single behavioral dimension, our proof-of-concept study presents a series of additional limitations that ought to be addressed in following studies. From a technical perspective, we utilized a relatively small sample size, which likely limited our ability to detect some of the significant differences, warranting additional experiments with increased power. Further studies are required to directly evaluate the use of our VR platform in each of the three prospective areas of application: preliminary testing and assessment of O&M techniques, training of persons with VI in O&M techniques, and education of the general public.

From the point of view of performance assessment, our study is limited to only two metrics: tasks completion time and total number of collisions. Researchers have used various methods to score travel performance of persons

with VI in a VR environment, including eye and head movements, spatial orientation, reading for distance and near, maximum recognition distance, etc. (Jones et al, 2020; Gopalakrishnan et al, 2020; Krösl et al, 2018). While orientation errors can be easily evaluated, other measurements are difficult to perform in VR, partly because of the need of more sophisticated systems to accurately track head and eye movements and to correctly measure reading capabilities. Moreover, most of the existing approaches deal only with the mobility aspect of the travel problem; few efforts have been made to measure the orientation aspect of travel skills (Virgili and Rubin, 2010). Challenges in specifying and implementing standard travel routes across different localities, problems in the definition of metrics that would be valid for all routes, and technical hardships in incorporating orientation and mobility measurement have hindered the standardization of measures of performance (Virgili and Rubin, 2010).

With respect to the use of our VR platform for preliminary testing and assessment of O&M techniques, we envision additional experiments with persons with VI suffering from glaucoma. By comparing performance of participants affected by glaucoma with those of participants performing the virtual O&M path with simulated glaucoma, we may expect the first group to show superior O&M skills (Barclay, 2011). In fact, participants affected by glaucoma are likely to have already developed sensory substitution to integrate auditory, cognitive, and auditory cues into O&M information. When participants with VI travel along our virtual O&M path, realistic and spatialized auditory cues could provide a memory map to assist with route planning and recognition of key environmental information (Barclay, 2011). On the contrary, healthy participants experiencing a simulated VI are not accustomed to compensate for vision loss with other senses, and may need the aid of additional and more specific audio instructions to effectively complete the virtual O&M path. Analyzing the differences between the performance of these two sets of participants could help us further refine our simulation of glaucoma, toward accurately reproducing the pathophysiology of this condition. To this end, we will finely tune the parameters in our glaucoma simulation toward matching the difference in performance of real glaucoma participants performing the virtual O&M path without simulated glaucoma.

Likewise, we plan to design new experiments involving both patients with real VI and O&M trainers. In these experiments, we will test how persons with VI perform in virtual O&M tasks, before and after O&M training sessions in our VR platform. Particular attention will be placed in assessing potential VR sickness effects in participants with VI. We expect that after repeated exposure to our VR platform users may habituate to the given visual motion stimulation (Palmisano and Constable, 2022). Habituation to VR sickness is described as a phenomenon that might occur during repeated exposure to the same visual motion stimulation or virtual environment leading to a reduction of the discomforts (Palmisano and Constable, 2022). After some tenable initial discomfort, persons with VI are likely to become acquainted to our system, thereby benefiting from the training. We will also consider the integration

of sensing and haptic feedback devices within our VR platform, which may be helpful to increase the sense of embodiment and support navigation and obstacle avoidance of persons with VI.

Developing games as health applications using VR then requires a broad intersection of theoretical and technical lenses. These include biomedical and psychosocial perspectives on health, computer and engineering technologies, human- computer interaction theory, and ultimately game design aimed to foster engagement. Our work makes a first, preliminary step toward the use of VR in O&M training for persons with VI, by creating a generalized platform that can be used to simulate different pathologies and realistic, complex O&M tasks within both indoor and outdoor environments.

Acknowledgements

We would also like to show our gratitude to Dr. Duane Geruschat, Research Associate in Ophthalmology at Johns Hopkins University Wilmer Eye Institute; and to Dr. William H. Seiple, Research Professor in Ophthalmology at NYU Grossman School of Medicine, for the insightful comments offered. Their knowledge and expertise shared with us during the course of this research, have greatly assisted this study and improved the manuscript.

Author Contributions

FSR designed the virtual reality platform, conducted the experiments, and performed statistical analyses. FSR and AB wrote the first draft of the manuscript. FSR, AB, JRR, and MP contributed to the investigation and framing of the results. JRR and MP supervised the research, secured the funding, and edited the first draft. MP managed the project. All the authors participated in the human subject protocol and reviewed and approved the final version of the manuscript.

Declarations

Funding

This study was supported by the National Science Foundation under award number CBET-1604355, ECCS-1928614, and CNS-1952180.

Conflicts of interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request from the Corresponding Author.

References

- Abich J, Parker J, Murphy JS, et al (2021) A review of the evidence for training effectiveness with virtual reality technology. *Virtual Reality* 25:1–15
- Albrecht T, Mattler U (2012) Individual differences in metacontrast masking regarding sensitivity and response bias. *Consciousness and Cognition* 21(3):1222–1231
- Allison K, Patel D, Besharim C (2021) The value of annual glaucoma screening for high-risk adults ages 60 to 80. *Cureus* 13(10)
- Alma MA, Van der Mei SF, Melis-Dankers BJ, et al (2011) Participation of the elderly after vision loss. *Disability and Rehabilitation* 33(1):63–72
- Ballemans J, Zijlstra GR, van Rens GH, et al (2012) Usefulness and acceptability of a standardised orientation and mobility training for partially-sighted older adults using an identification cane. *BMC Health Services Research* 12(1):1–14
- Barak Ventura R, Porfiri M (2020) Galvanic skin response as a measure of engagement during play in virtual reality. In: *Dynamic Systems and Control Conference*, American Society of Mechanical Engineers, p V001T17A003
- Barak Ventura R, Richmond S, Nadini M, et al (2021) Does winning or losing change players’ engagement in competitive games? experiments in virtual reality. *IEEE Transactions on Games* 13(1):23–34
- Barclay LA (2011) Learning to listen/listening to learn: teaching listening skills to students with visual impairments. *American Foundation for the Blind*
- Bergström I, Kiltani K, Slater M (2016) First-person perspective virtual body posture influences stress: a virtual reality body ownership study. *PLOS ONE* 11(2):e0148,060
- Biocca F (1999) The cyborg’s dilemma: Progressive embodiment in virtual environments. *Human Factors in Information Technology* 13:113–144
- Boldini A, Ma X, Rizzo JR, et al (2021) A virtual reality interface to test wearable electronic travel aids for the visually impaired. In: *Nano-, Bio-, Info-Tech Sensors and Wearable Systems*, International Society for Optics and Photonics, p 115900Q
- Bormann K (2006) Subjective performance. *Virtual Reality* 9(4):226–233
- Bowditch J (2021) Eye tracking. In: *The Power of Virtual Reality Cinema for Healthcare Training*. Productivity Press, p 75–80

- Brouwer DM, Sadlo G, Winding K, et al (2008) Limitations in mobility: experiences of visually impaired older people. *British Journal of Occupational Therapy* 71(10):414–421
- Bruce B. Blasch RLEWWilliam R. Wiener (1997) *Foundations of orientation and mobility*, 2nd edn. AFB Press, New York
- Burton MJ, Ramke J, Marques AP, et al (2021) The Lancet Global Health Commission on global eye health: Vision beyond 2020. *The Lancet Global Health* 9(4):e489–e551
- Campisi T, Ignaccolo M, Inturri G, et al (2021) Evaluation of walkability and mobility requirements of visually impaired people in urban spaces. *Research in Transportation Business & Management* 40:100,592
- Chou CF, Frances Cotch M, Vitale S, et al (2013) Age-related eye diseases and visual impairment among U.S. adults. *American Journal of Preventive Medicine* 45(1):29–35
- Congdon N, O’Colmain B, Klaver C, et al (2004) Eye diseases prevalence research group. Causes and Prevalence of Visual Impairment Among Adults in the United States 122:477–485
- David N, Newen A, Vogeley K (2008) The “sense of agency” and its underlying cognitive and neural mechanisms. *Consciousness and Cognition* 17(2):523–534
- Demmin DL SS (2020) Visual impairment and mental health: Unmet needs and treatment options. *Clinical Ophthalmology* 14:4229–4251
- Dowling J, Maeder A, Boles W (2003) Intelligent image processing constraints for blind mobility facilitated through artificial vision. In: 8th Australian & New Zealand Intelligent Information Systems Conference, Queensland University of Technology, pp 109–114
- Everett AH, Ponder P (1976) *Orientation and Mobility Techniques: A Guide for the Practitioner*. Amer Foundation for the Blind
- Figg B (2021) National Eye Institute. *Journal of Consumer Health on the Internet* 25(2):187–195
- GBD 2019 Blindness and Vision Impairment Collaborators, Vision Loss Expert Group of the Global Burden of Disease Study, Bourne R, et al (2021) Trends in prevalence of blindness and distance and near vision impairment over 30 years: an analysis for the global burden of disease study. *The Lancet Global Health* 9(2):e130–e143

- Ghali NI, Soluiman O, El-Bendary N, et al (2012) Virtual reality technology for blind and visual impaired people: reviews and recent advances. In: *Advances in Robotics and Virtual Reality*. Springer, p 363–385
- Gol S, Pena RN, Rothschild MF, et al (2018) A polymorphism in the fatty acid desaturase-2 gene is associated with the arachidonic acid metabolism in pigs. *Scientific Reports* 8(1):1–9
- Goldschmidt M (2018) *Orientation and Mobility Training to People with Visual Impairments*, Springer International Publishing, Cham, pp 237–261
- González-Franco M, Peck TC, Rodríguez-Fornells A, et al (2014) A threat to a virtual hand elicits motor cortex activation. *Experimental Brain Research* 232(3):875–887
- Gopalakrishnan S, Jacob CES, Kumar M, et al (2020) Comparison of visual parameters between normal individuals and people with low vision in a virtual environment. *Cyberpsychology, Behavior, and Social Networking* 23(3):171–178
- Gordois A, Cutler H, Pezzullo L, et al (2012) An estimation of the worldwide economic and health burden of visual impairment. *Global Public Health* 7(5):465–481
- Gorisse G, Christmann O, Amato EA, et al (2017) First-and third-person perspectives in immersive virtual environments: presence and performance analysis of embodied users. *Frontiers in Robotics and AI* 4:33
- Haegele JA, Zhu X (2021a) Movement behaviors, comorbidities, and health-related quality of life among adults with visual impairments. *Disability and Rehabilitation* pp 1–7
- Haegele JA, Zhu X (2021b) Physical activity, self-efficacy and health-related quality of life among adults with visual impairments. *Disability and Rehabilitation* 43(4):530–536
- Hawkins AS, Szlyk JP, Ardickas Z, et al (2003) Comparison of contrast sensitivity, visual acuity, and Humphrey visual field testing in patients with glaucoma. *Journal of Glaucoma* 12(2):134–138
- Heinrich C, Cook M, Langlotz T, et al (2021) My hands? Importance of personalised virtual hands in a neurorehabilitation scenario. *Virtual Reality* 25(2):313–330
- Houzangbe S, Christmann O, Gorisse G, et al (2020) Effects of voluntary heart rate control on user engagement and agency in a virtual reality game. *Virtual Reality* 24(4):665–681

- Hu CX, Zangalli C, Hsieh M, et al (2014) What do patients with glaucoma see? Visual symptoms reported by patients with glaucoma. *The American Journal of the Medical Sciences* 348(5):403–409
- Jones GC, Crews JE, Danielson ML (2010) Health risk profile for older adults with blindness: an application of the international classification of functioning, disability, and health framework. *Ophthalmic Epidemiology* 17(6):400–410
- Jones PR, Somoskeöy T, Chow-Wing-Bom H, et al (2020) Seeing other perspectives: evaluating the use of virtual and augmented reality to simulate visual impairments (openvissim). *NPJ Digital Medicine* 3(1):1–9
- Judd CM, McClelland GH, Ryan. CS (2017) *Data analysis : a model comparison approach to regression, ANOVA, and beyond*, 3rd edn. Routledge, New York, N.Y.
- Kennedy RS, Stanney KM, Dunlap WP (2000) Duration and Exposure to Virtual Environments: Sickness Curves During and Across Sessions. *Presence: Teleoperators and Virtual Environments* 9(5):463–472
- Kilteni K, Groten R, Slater M (2012) The sense of embodiment in virtual reality. *Presence Teleoperators & Virtual Environments* 21
- Kim HN (2021) Older adults with visual disabilities and fear of falling associated with activities of daily living. *International Journal of Human Factors and Ergonomics* 8(1):64–84
- Klinger E, Weiss PL, Joseph PA (2010) *Virtual reality for learning and rehabilitation*, Springer Paris, Paris, pp 203–221
- Krösl K, Bauer D, Schwärzler M, et al (2018) A vr-based user study on the effects of vision impairments on recognition distances of escape-route signs in buildings. *The Visual Computer* 34(6):911–923
- LaGrow SJ, Weessies MJ (1994) *Orientation and mobility: Techniques for independence*. Dunmore Press Palmerston North, New Zealand
- Lahav O, Mioduser D (2005) Blind persons' acquisition of spatial cognitive mapping and orientation skills supported by virtual environment. *International Journal on Disability and Human Development* 4(3):231–238
- Lahav O, Schloerb D, Kumar S, et al (2012) A virtual environment for people who are blind—a usability study. *Journal of Assistive Technologies* 6(1)
- Lahav O, Schloerb DW, Srinivasan MA (2015) Rehabilitation program integrating virtual environment to improve orientation and mobility skills for

people who are blind. *Computers & Education* 80:1–14

Lin JH, Peng W (2015) The contributions of perceived graphic and enactive realism to enjoyment and engagement in active video games. *International Journal of Technology and Human Interaction (IJTHI)* 11(3):1–16

Marques AP, Ramke J, Cairns J, et al (2021) Global economic productivity losses from vision impairment and blindness. *EClinicalMedicine* 35:100,852

Matamala-Gomez M, Donegan T, Bottiroli S, et al (2019) Immersive virtual reality and virtual embodiment for pain relief. *Frontiers in Human Neuroscience* 13:279

Matthews G, Campbell SE, Falconer S, et al (2002) Fundamental dimensions of subjective state in performance settings: Task engagement, distress, and worry. *Emotion* 2(4):315

Mouatt B, Smith AE, Mellow ML, et al (2020) The use of virtual reality to influence motivation, affect, enjoyment, and engagement during exercise: A scoping review. *Frontiers in Virtual Reality* 1:39

Newport R, Pearce R, Preston C (2010) Fake hands in action: embodiment and control of supernumerary limbs. *Experimental Brain Research* 204(3):385–395

Oculus Safety Center (2021) Oculus Quest Safety & Warranty Manual. URL <https://www.oculus.com/safety-center/quest/>

Padrao G, Gonzalez-Franco M, Sanchez-Vives MV, et al (2016) Violating body movement semantics: Neural signatures of self-generated and external-generated errors. *Neuroimage* 124:147–156

Paliokas I, Kalamaras E, Votis K, et al (2020) Using a virtual reality serious game to assess the performance of older adults with frailty. *Advances in experimental medicine and biology* 1196:127–139

Palmisano S, Constable R (2022) Reductions in sickness with repeated exposure to hmd-based virtual reality appear to be game-specific. *Virtual Reality* pp 1–17

Rokach A, Berman D, Rose A (2021) Loneliness of the blind and the visually impaired. *Frontiers in Psychology* 12

Salamin P, Tadi T, Blanke O, et al (2010) Quantifying effects of exposure to the third and first-person perspectives in virtual-reality-based training. *IEEE Transactions on Learning Technologies* 3(3):272–276

- Sansone L, Stanzani R, Job M, et al (2021) Robustness and static-positional accuracy of the steamvr 1.0 virtual reality tracking system. *Virtual Reality*
- Shoureshi RA, Rizzo JR, Hudson TE (2017) Smart wearable systems for enhanced monitoring and mobility. In: *Advances in Science and Technology*, Trans Tech Publ, pp 172–178
- Slater M, Sanchez-Vives MV (2016) Enhancing our lives with immersive virtual reality. *Frontiers in Robotics and AI* 3:74
- Slater M, Spanlang B, Corominas D (2010a) Simulating virtual environments within virtual environments as the basis for a psychophysics of presence. *ACM Transactions on Graphics (TOG)* 29(4):1–9
- Slater M, Spanlang B, Sanchez-Vives MV, et al (2010b) First person experience of body transfer in virtual reality. *PLOS ONE* 5(5):e10,564
- Soong GP, Lovie-Kitchin JE, Brown B (2001) Does mobility performance of visually impaired adults improve immediately after orientation and mobility training? *Optometry and Vision Science* 78(9):657–666
- Stamper RL, Lieberman MF, Drake MV (1970) *Becker-Shaffer’s diagnosis and therapy of the glaucomas*. Mosby, Elsevier
- Stein JD, Khawaja AP, Weizer JS (2021) Glaucoma in adults—screening, diagnosis, and management: A review. *JAMA* 325(2):164–174
- Tao G, Garrett B, Taverner T, et al (2021) Immersive virtual reality health games: a narrative review of game design. *Journal of NeuroEngineering and Rehabilitation* 18
- Toombs SK (2001) *Handbook of phenomenology and medicine*, vol 68. Springer Science & Business Media
- Tsakiris M, Longo MR, Haggard P (2010) Having a body versus moving your body: neural signatures of agency and body-ownership. *Neuropsychologia* 48(9):2740–2749
- Virgili G, Rubin G (2010) Orientation and mobility training for adults with low vision. *Cochrane Database of Systematic Reviews* (5)
- Wiener W, Lawson G, Naghshineh K, et al (1997) The use of traffic sounds to make street crossings by persons who are visually impaired. *Journal of Visual Impairment & Blindness* 91(5):435–445
- World Health Organization (2019) *World report on vision*

- Wu H, Ashmead DH, Adams H, et al (2018) Using virtual reality to assess the street crossing behavior of pedestrians with simulated macular degeneration at a roundabout. *Frontiers in ICT* 5:27
- Xie L, Antle AN, Motamedi N (2008) Are tangibles more fun? Comparing children's enjoyment and engagement using physical, graphical and tangible user interfaces. In: *Proceedings of the 2nd International Conference on Tangible and Embedded Interaction*, pp 191–198
- Zhao Y, Cutrell E, Holz C, et al (2019) Seeingvr: A set of tools to make virtual reality more accessible to people with low vision. pp 1–14