Vision Impairment Provides New Insight Into Self-Motion Perception

Wilson Luu,[1,2] Barbara Zangerl,[1,2] Michael Kalloniatis,[1,2] Stephen Palmisano,[3] and Juno Kim[1]

[1]School of Optometry and Vision Science, University of New South Wales, Sydney, Australia
[2]Centre for Eye Health, University of New South Wales, Sydney, Australia
[3]School of Psychology, University of Wollongong, Wollongong, Australia

Correspondence: Wilson Luu, Centre for Eye Health, School of Optometry and Vision Science, South Wing, Rupert Myers Building, UNSW Sydney, NSW 2052, Australia; wilson.luu@unsw.edu.au.
Juno Kim, School of Optometry and Vision Science, Level 3, Room 3.006, North Wing, Rupert Myers Building, UNSW Sydney, NSW 2052, Australia; juno.kim@unsw.edu.au.

Received: September 20, 2020
Accepted: January 15, 2021
Published: February 3, 2021

Citation: Luu W, Zangerl B, Kalloniatis M, Palmisano S, Kim J. Vision impairment provides new insight into self-motion perception. *Invest Ophthalmol Vis Sci.* 2021;62(2):4. https://doi.org/10.1167/iovs.62.2.4

Purpose. Leading causes of irreversible blindness such as age-related macular degeneration (AMD) and glaucoma can, respectively, lead to central or peripheral vision loss. The ability of sufferers to process visual motion information can be impacted even during early stages of eye disease. We used head-mounted display virtual reality as a tool to better understand how vision changes caused by eye diseases directly affect the processing of visual information critical for self-motion perception.

Methods. Participants with intermediate AMD or early manifest glaucoma with near-normal visual acuities and visual fields were recruited for this study. We examined their experiences of self-motion in depth (linear vection), spatial presence, and cybersickness when viewing radially expanding patterns of optic flow simulating different speeds of self-motion in depth. Viewing was performed with the head stationary (passive condition) or while making lateral-sway head movements (active conditions).

Results. Participants with AMD (i.e., central visual field loss) were found to have *greater* vection strength and spatial presence, compared to participants with normal visual fields. However, participants with glaucoma (i.e., peripheral visual field loss) were found to have *lower* vection strength and spatial presence, compared to participants with normal visual fields. Both AMD and glaucoma groups reported reduced severity in cybersickness compared to healthy normals.

Conclusions. These findings strongly support the view that perceived self-motion is differentially influenced by peripheral versus central vision loss, and that patients with different visual field defects are oppositely biased when processing visual cues to self-motion perception.

Keywords: virtual reality, vection, presence, age-related macular degeneration, glaucoma

Visual motion processing is critical for perceiving and controlling our self-motion through the world in a variety of situations (e.g., walking or driving a car). However, motion perception is a visual function that is not routinely assessed in clinical settings. Glaucoma and age-related macular degeneration (AMD) are both leading causes of severe vision loss and legal blindness in both Australia and worldwide.[1–3] Early detection is particularly important, because De Moraes and colleagues[4] found that even a 30% loss in visual fields can have a significant impact on health-related quality of life. Because motion perception is typically associated with peripheral visual field, it is often overlooked in those with AMD. In early stages of glaucoma, functional vision loss may not be detectable, particularly in cases of preperimetric glaucoma.[5] Although visual acuity typically remains intact in earlier stages, complete vision loss occurs if left untreated.[6] It is estimated that 50% of people with glaucoma remain undetected.[7,8] This may also hold true with motion perception because numerous studies have shown that motion perception was impaired despite normal visual acuity and visual field results.[9,10] In this study, we consider the functional implications of central and peripheral visual field impairments on the processing of visual motion in the perception of self-motion.

Normal healthy visual perception of self-motion depends on the neural processing of optic flow information that is generated when we move relative to other objects in the environment.[11] Research on self-motion perception has often studied illusory self-motion generated by visual displays that present optic flow patterns that artificially simulate different forms of self-motion to stationary participants.[12] "Vection" is the term used to describe these visual illusions of self-motion.[12] Although these illusions have been traditionally induced and examined in stationary observers, vection is now increasingly examined in active, moving observers.[12] These illusions are important for understanding how individuals visually perceive (and control) their self-motion through the environment. The visual stimulus for vection is global optical flow.[11] Because this stimulus provides information about the relative motion between the observer and his/her surrounding environment, deficits in optic flow processing can distort the perception of self-motion. Studies have found that the experience of vection depends on the characteristics of this optic flow (i.e., the

area of visual motion stimulation, the spatial and temporal frequency, the presence of visual jitter, and even the exposure time).[13–19] Eye movements are also known to have an effect on vection by altering the observer's retinal motion, which can alter the perceived strength and direction of vection.[20–24] These perceived vection biases also affect the perceived distance travelled and can also influence gait and walking speeds.[25–27] Hence, the visual perception of self-motion and behavioral responses to this information depends not only on optic flow, but also on the complex pattern of eye movements and the precise pattern of retinal motion generated across a participant's visual field.

Research has shown that the stimulation of the peripheral visual field plays an important role in the experience of vection. Brandt et al.,[28] who originally proposed the "peripheral dominance theory," compared the vection induced by stimulating their observer's central and peripheral visual fields with optic flow consistent with self-rotation (circular vection). Their findings supported the notion of two distinct features of motion processing, which they deemed as focal (object perception and motion) and ambient (posture and self-motion). Subsequent studies assessing circular vection have maintained the proposal that object motion is primarily driven by the central visual field, and visually induced self-motion and body orientation are driven by the peripheral visual fields.[13,28] The impact of the peripheral visual field on vection is further highlighted by Keshavarz and colleagues,[29] who found that a large dome-like display or multiple displays arranged in a three-dimensional (3D) structure generated stronger experiences of vection compared with a single screen displayed centrally. However, Palmisano and Gillam[30] reported that circular vection is influenced by the interaction of the spatial frequency of optic flow and the eccentricity of the visual stimuli. They showed that most compelling vection was experienced when high spatial frequency patterns were presented centrally and low spatial frequency patterns were presented peripherally. However, this study did not use stable central fixation, but rather a fixation guide that allowed the eyes to move over a short range.

Other researchers conducting studies on linear vection have shown that vection can be induced by stimulating the central visual field, and that the experience of visually induced self-motion may actually be independent from the retinal eccentricity of the motion stimulation.[17,30,31] For example, Andersen and Braunstein[17] explored the effects of both the speed and location of motion stimuli (by varying different visual angles in the central radial flow field simulating linear self-motion in depth) to see at which point self-motion is induced. They were able to elicit the experience of self-motion by stimulating small areas of the central visual field using a radially expanding pattern in depth. Their success in inducing self-motion in depth was attributed to the optic flow pattern representing 3D structure in depth. Similarly, Nakamura and Shimojo[32] found that centrally presented visual motion with stable fixation generated magnitudes of horizontal linear vection that were at least as strong as observed with peripherally presented motion of the same optical size. Tarita-Nistor et al. [33] explored the role of central fixation on the processing of radially expanding motion simulating linear self-motion in depth. They found that vection strength was similar during central and peripheral motion during stable central fixation. When participants viewed displays freely without fixation, vection for peripheral motion was unchanged, but vection increased in response to centrally presented motion.[33] Hence, vection appears to invariably depend on peripheral visual motion but may be modulated by central visual motion information during fixation.

Ocular diseases causing vision impairment in the form of field loss may differentially influence the visual processing of central and peripheral motion information for the perception of self-motion. Whereas eye diseases such as age-related macular degeneration (AMD) impact the central visual field, eye diseases such as glaucoma impact the peripheral visual field. Given that there may be differential effects of these central and peripheral impairments on motion processing, it has become clinically valuable for vision scientists to consider how these vision impairments affect the perception of self-motion.

Virtual reality (VR) appears to provide a convenient, portable and safe method to systematically alter the pattern of retinal motion generated by optic flow when observers are immersed in realistic virtual environments.[34,35] Much of the previous research on vection has used either large physical devices (such as rotating drums or swinging rooms) or presented visual motion stimulation to observers using large computer-generated external displays.[13,15,30] Only recently have there been studies using head-mounted displays (HMDs) to vection in depth.[36–39] The portability of these devices offers improved accessibility for evaluating visual function. Recent HMD VR studies with patients have found that motion perception is either similar[40] or enhanced[41] in those with bilateral central vision loss caused by AMD, compared with normal vision. It was postulated that those with AMD are more sensitive to their peripheral vision because of compensation of the deficit in their central visual field. In other work with patients having early stage glaucoma (i.e., a decline in peripheral visual field sensitivity), researchers presented rotatory visual motion simulating angular rotation around the viewing axis on the Oculus Rift HMD.[42] No difference in vection strength was found between glaucoma patients and controls on vection strength estimates. However, they did find that patients with early-stage glaucoma had longer vection onset latencies (indicative of poorer vection), compared to age-matched normal participants. Hence, motion perception appears to be a potentially valuable area of clinical testing apart from conventional means, which could play more of a role in earlier detection and management of ocular diseases.

One potential limitation of the use of HMD VR in vision assessment is their potential to generate *cybersickness*—the adverse symptoms include nausea, dizziness, and other asthenopic and motion sickness–like symptoms.[37,43–45] The degree to which participants report experiences of cybersickness appears to depend on the amount of sensory conflict that is generated between visual and vestibular systems.[46,47] For example, increasing the display lag in updating the visual scene generates sensory incompatibility between visually simulated head movements and physically sensed head movement by the vestibular system.[48–50] Another potential implication of visual field defects on perception is the experience of *spatial presence*—the experience of "being there" in the virtual environment.[51–53] In recent work, the magnitude of spatial presence was found to decline under conditions where cybersickness had reportedly increased.[50] It is possible that the dependence of presence on sensory conflict might be differentially influenced by different types of visual field defects. Despite numerous studies investigating vection, presence, and cybersickness in

Investigative Ophthalmology & Visual Science

Table. Characteristics of Observers

	Normal	Glaucoma	Age-Related Macular Degeneration	Total
No. of participants	16	19	17	52
Mean Age ± SD	66.06 ± 9.05	66.84 ± 6.30	66.41 ± 7.21	66.49 ± 7.32
No. of females (males)	5 (11)	8 (11)	10 (7)	23 (29)
Mean Binocular Visual Acuity (LogMAR) ± SD	0.08 ± 0.12	0.08 ± 0.08	0.09 ± 0.11	0.09 ± 0.11
*Stereoacuity (Arcsec) ± SD	55.60 ± 26.82	77.67 ± 45.39	71.25 ± 45.49	79.46 ± 73.64
Mean Deviation (dB) ± SD	—		—	—
Right		−2.10 ± 1.58		
Left		−1.68 ± 1.58		

SD, standard deviation.
* Mean stereoacuity and standard deviation calculated in participants who could perceive global stereopsis.

HMDs, there has been limited research in this area involving participants with eye diseases affecting different parts of the visual field.

In this study, we focused on the impact of AMD and glaucoma on vection, presence and cybersickness measures. Observers were presented with a display showing a radial flow pattern simulating self-motion in depth in HMD VR. They viewed these displays while having their head stationary or while generating active head movements with or without ecological compensation (i.e., whether the radial flow display compensated for head movements). We manipulated ecological compensation to systematically vary the degree of visual-vestibular sensory conflict generated when viewing the visual displays.[19,54] We expected that increasing sensory conflict would reduce vection strength.[46,55] We further expected that the increases in sensory conflict would increase the likelihood and severity of reported cybersickness[48,49] and reduce the experience of spatial presence.[50,51,56] We hypothesized that those with early manifest glaucoma would experience reduced vection strength, presence, and cybersickness compared with those without known eye disorders. This prediction was anticipated because of their associated deficit in peripheral visual field sensitivity. It was also hypothesized that those with AMD would experience similar or enhanced vection strength, presence and cybersickness compared with those without known eye disorders as the sensitivity of their peripheral visual field would be maintained.

Method

Procedures were approved by the Human Research Ethics Advisory panel at University of New South Wales. All procedures were conducted in accordance with the Human Research Ethics Advisory panel at University of New South Wales Sydney guidelines and regulations and approved protocol, as well as adhered to the tenets of the Declaration of Helsinki. Informed written consent was received by all participants.

Participants

Fifty-two naïve adults (23 females and 29 males) between the ages of 51 and 80 (66.49 years old ± 7.32) participated in this study. All participants had visual acuities of LogMAR 0.3 (Snellen 6/12) or better in the worse eye with or without correction (legal requirement for private unconditional driving in Australia). They had no prior vestibular dysfunction and were not prone to motion sickness. Participants who were diagnosed with either early glaucoma by an ophthalmologist (glaucoma subspecialty) or intermediate age-related macular degeneration in both eyes by optometrists using the Beckman classification scale,[57] were recruited from the Centre for Eye Health Glaucoma Management Clinic or General Clinic (see Ly et al. for glaucoma[58] and retinal[59] clinic models), respectively. Criteria for diagnoses were set after consultation with ophthalmologists. Those with intermediate AMD were diagnosed based on structural findings of having large drusen > 125 µm or any macular pigmentary abnormalities and absence of any neovascularization or geographic atrophy. Participants with glaucoma were diagnosed by structural assessment of the optic nerve and nerve fiber layer in combination with functional outcome measures (mean deviation, pattern standard deviation and glaucoma hemifield test) from the Humphrey Visual Field Analyser 3 (Carl Zeiss Meditec, Dublin, CA, USA) using SITA-Standard 24-2 paradigm. The Mills criteria[60] was used to categorize of glaucoma severity. Those with no pathology were recruited by responding to an advertisement distributed across Sydney, Australia, and via social media. All participants were screened for their visual acuity using a standard Bailey-Lovie LogMAR Chart calibrated for 3 m, with their stereo-acuity using a Random Dot Stereo Acuity Chart with Lea Symbols (Vision Assessment Corporation, 2007), observer's pupillary distance, and ocular health by an experienced clinician. Participants were excluded if they had a history of amblyopia, strabismus or cataracts worse than grade 2. Participant characteristics are shown below in the Table. Additional participant vision functions are shown in Supplementary Table S1.

Display Generation

Displays simulating illusory self-motion in depth (vection) while facing forward (pure radial optic flow) were created using our custom software developed using Visual C++ and Microsoft Visual Studio 2010. This software used OpenGL and the Oculus Rift CV1 SDK. A spherical 3D cloud (of radius approximately 3 m) was populated with 18,432 blue squares (ranging in optical size from 0.25° to 2.5° with proximity to the observer) and was simulated to surround the observer. The blue squares moved in a radial pattern from a focus of expansion at varying stepwise speeds (either 0, 1, 2, or 3 m/s). A small green central target was used to orient observers to ensure they were facing the appropriate direction. A fixation target (small white dot) was set slightly below the focus of expansion. A baseline modulus was developed as a reference (passive viewing with set speed "2 m/s") for observers to view before the trials. Each speed setting was calibrated so that the blue squares would travel in their

respective meters/second (m/s). Three questions appeared directly, after each self-motion simulation, which were used to rate the participant's vection, presence and cybersickness for the trial. Vection was rated on a vertical scale ranging from 0 (completely stationary) to 100 (if they felt they were moving like if they were sprinting). Presence was rated on a vertical scale between 0 (completely disconnected from the virtual world and still feel like they're in the physical world) and 20 (completely within the virtual world) and was based on previous published studies.[61,62] Cybersickness was rated based on the Fast Motion Sickness scale.[63]

The experiment consisted of a total of 12 trials (with all speed settings) presented in randomized order. Each trial was presented for 30 seconds. Displays either generated pure radial optic flow without head movements (passive viewing) or pure radial optic flow despite head movements (active uncompensated viewing) or were compensated for head movements consistent with a constant spatial direction of self-motion (active compensated viewing). Passive viewing and active compensated viewing conditions produced little or no visual-vestibular conflict whereas active uncompensated viewing conditions generated sustained visual-vestibular conflict. An audible tone was delivered to the Rift's earpiece at a rate of 1 Hz for eight of the trials. The audible tone signaled for the observer to sway (active viewing) at the rate of metronomic sound. Yaw, pitch, and roll changes in head orientation were recorded for all trials using the Rift's inherent accelerometers and gyros and were computed as Euler angles in degrees.

Procedure

The Oculus Rift (CV1) HMD pupillary distance was adjusted to match the pupillary distance measured during screening. Participants only wore their distance optical correction (if any). Each participant was seated, and the HMD was placed on the observer until a comfortable fit was achieved. The observer was asked to adjust the head-mounted device vertically until the Oculus Home page was most clear. The device was then tightened to a comfortable point using the attached Velcro.

The experimenter instructed the observer of the steps involved in the example and experiment. The experimenter initiated the example modulus trial to the observer before the experimental trial to ensure they understood the task, as well as provide a baseline comparison. During each of the displays, the observer was asked to orient themselves using the green central target. They were then asked to fixate on the white fixation target during the presentation and concentrate on the experience (if any) of illusory self-motion in depth. The observer was asked to sway (interaural translational head movements) when an audible metronomic tone was heard in the earpiece of the Oculus Rift and remain stationary when there were no audible tones. The observer was asked to grade the level of vection, presence, and whether they felt sick in order to get used to the method of answering using the directional keys and spacebar on the provided keyboard.

Statistical Analyses

Analyses were performed using the statistical programming language R (R version 3.6.1; Foundation for Statistical Computing, Vienna, Austria) and GraphPad Prism (Version 8.0.0; GraphPad Software, Inc., San Diego, CA, USA).

Results

Head Movement Analysis

Participant head movements were analyzed (detailed in Supplementary S1 and Fig. S1) to ensure that any eye group effects on vection, presence, and cybersickness were due to their visual function and perception (as opposed to differences in their head movements). Similarly we wanted to ensure that head movements amplitudes and frequencies were comparable in the compensated and uncompensated active viewing conditions. We examined the variance of head movements using two-way analysis of variance (ANOVA) and found no significant differences within each eye group for each speed ($F_{3,45} = 0.62$, $P = 0.60$) and viewing conditions ($F_{1,15} = 1.97$, $P = 0.18$). No significant differences were also found using unpaired two-tailed *t*-tests between the AMD ($t_{31} = 1.57$, $P = 0.13$) and glaucoma groups ($t_{33} = 0.96$, $P = 0.34$) with the normal groups.

We then examined whether perceived vection strength, spatial presence, and cybersickness varied across the three active/passive viewing conditions and the four simulated speeds in healthy participants without known eye disorders, participants with intermediate AMD, and participants with glaucoma (Fig. 1).

Vection Strength

Vection strength increased with increasing simulated speed of self-motion for all viewing conditions in each group (Figs. 1a–1c). Perceived vection strengths were similar across all viewing conditions except the slow speed passive viewing condition (Fig. 1b). Three-way mixed model ANOVA was performed to compare the effects of simulated speeds and viewing condition across all eye condition groups on perceived vection strength.

We found main effects of simulated speed ($F_{3,147} = 356.61$, $P < 0.0001$) and eye condition group ($F_{2,49} = 13.52$, $P < 0.0001$) on perceived vection. A significant interaction between simulated speed and eye condition on perceived vection ($F_{6,147} = 6.00$, $P < 0.0001$) was also found. There was a trend for viewing condition to impact perceived vection; however, this was not significant ($F_{2,98} = 2.45$, $P = 0.09$). No other significant interactions were found between these variables.

Spatial Presence

Spatial presence slightly increased with increasing speed for each viewing condition in each group (Figs. 1d–1f). However, perceived spatial presence plateaued in the AMD group at higher speeds (Fig. 1e). A three-way mixed model ANOVA was performed to compare the effects of simulated speeds and viewing condition across all eye condition groups on perceived spatial presence.

A main effect of simulated speed ($F_{3,147} = 34.32$, $P < 0.0001$) was found on perceived spatial presence. There was an effect of viewing condition on perceived spatial presence, but this only just reached statistical significance ($F_{2,98} = 3.08$, $P = 0.05$). Eye conditions did not significantly impact perceived spatial presence ($F_{2,49} = 0.98$, $P = 0.38$). No significant interactions were found between these variables.

Investigative Ophthalmology & Visual Science

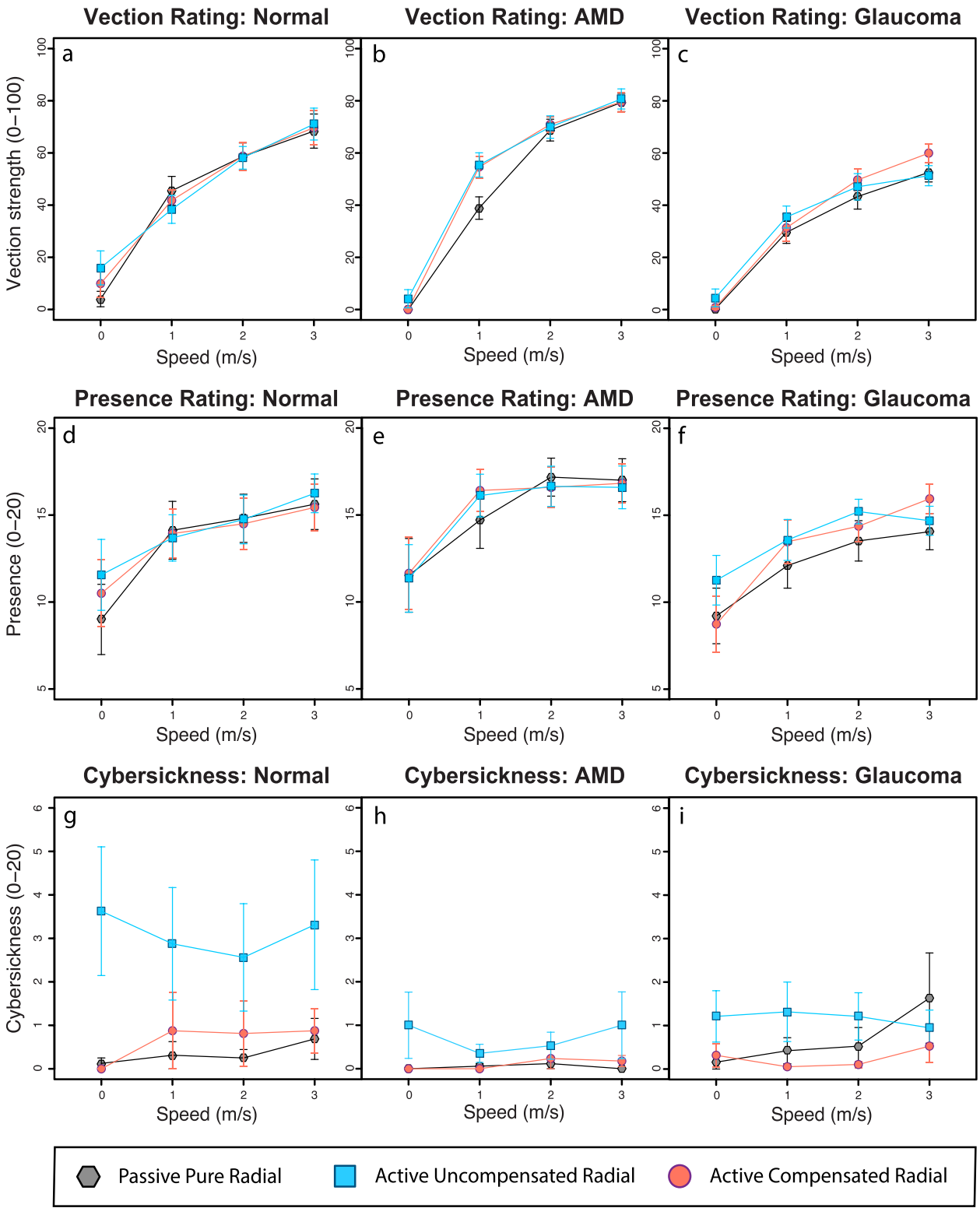

Figure 1. Mean vection (*top row*), spatial presence (*middle row*), and cybersickness ratings (*bottom row*) plotted as function of simulated speed for each of the viewing conditions (passive radial, active radial, and active compensation) and for each eye group (normal, age-related macular degeneration, and glaucoma). *Error bars*: Standard error of the mean.

Cybersickness

Cybersickness was similar across all speeds for each viewing condition in each group (Figs. 1g–1i). Participants typically reported either no symptoms or low severities in cybersickness. Cybersickness was greatest in the active uncompensated radial condition. A three-way mixed-model ANOVA was performed to compare the effects of simulated speeds

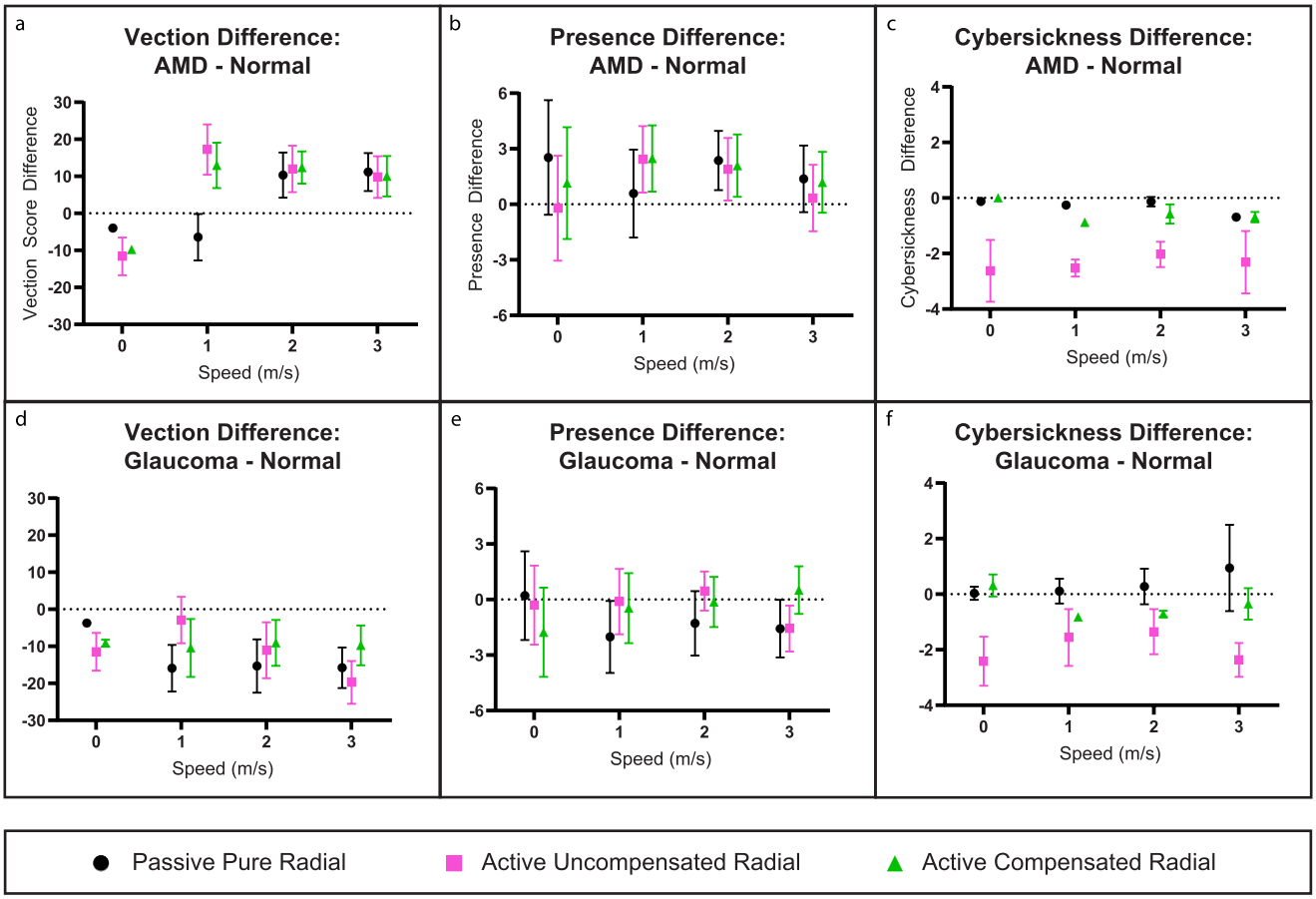

Figure 2. Difference plots for vection score (**a** and **d**), presence rating (**b** and **e**) and cybersickness (**c** and **f**) during passive and two active viewing conditions. *Top row:* Comparison between age-related macular degeneration group and healthy participants (**a, b**, and **c**). *Bottom row:* Comparison between glaucoma group and healthy participants (**d, e**, and **f**). *Error bars:* 95% CI.

and viewing condition across all eye condition groups on cybersickness.

Viewing conditions were found to have a main effect on cybersickness ($F_{2,98} = 9.83$, $P < 0.001$). There was also a significant interaction between viewing condition and eye condition on cybersickness ($F_{4,98} = 2.62$, $P < 0.05$). However, simulated speed ($F_{3,147} = 1.50$, $P = 0.22$) and eye condition ($F_{2,49} = 2.23$, $P = 0.12$) did not significantly impact cybersickness. Active uncompensated viewing conditions resulted in more severe cybersickness compared with active compensated and passive viewing conditions.

Correlation Statistics

Pearson's product-moment correlations were performed to compare the relationship between the above measures across all groups. There was a weak positive correlation between perceived vection strength and presence ($r = 0.30$, $P < 0.05$). The correlations between cybersickness and presence ($r = -0.05$, $P = 0.72$) and perceived vection strength ($r = 0.02$, $P = 0.86$) were not significant.

We performed further analyses to compare the differences of vection scores, perceived presence and cybersickness in all viewing conditions between either age-related macular degeneration or early manifest glaucoma groups with those without eye disease (Fig. 2). Those with intermediate AMD reported relatively higher vection scores compared with healthy participants when motion in depth was simulated (M = 11.99, 95% confidence interval [CI] [5.95, 18.04]) (Fig. 2a). However, these participants reported lower experiences of vection strength during all "no motion in depth" viewing conditions and low-speed passive viewing condition (M = −6.44, 95% CI [−12.49, −0.40]). They also perceived higher spatial presence in the low and middle simulated speeds (M = 2.09, 95% CI [0.47, 3.71]) (Fig. 2b). There was no statistical difference during low-speed passive viewing, and all no simulated speed and the fastest speed viewing conditions. Those with age-related macular degeneration also reported less experiences in cybersickness compared to healthy participants, particularly in active conditions (M = −2.03, 95% CI [−2.47, −1.60]). (Fig. 2c). We performed follow-up statistical analyses using N serial successes method to determine minimum population proportions[64] by comparing the differences of each successive participant from the mean normal response. It was extrapolated that 37% to 74% of those with intermediate AMD would have enhanced experience of vection during passive and active viewing of simulated motion in depth.

Those with early manifest glaucoma reported relatively lower vection scores compared with healthy participants (M = −11.07, 95% CI [−18.37, −3.77]) (Fig. 2d). Differences were significant for all viewing conditions and speeds except for the low speed active uncompensated viewing condition (M = −2.90, 95% CI [−8.97, 3.17]). They also reported

similar or lower perceived presence, particularly in the faster speeds of the passive and active uncompensated viewing conditions (M = −1.57, 95% CI [−2.77, −0.37]) (Fig. 2e). Those with early manifest glaucoma also experienced either similar or less cybersickness compared to healthy participants (M = −1.35, 95% CI [−2.14, −0.57]) (Fig. 2f). Similarly, it was extrapolated that at least 37% to 74% of those with early glaucoma would have lower experiences of vection.

Discussion

In this study, we demonstrated the effects on self-motion perception of early eye diseases that differentially affect central or peripheral visual fields. Our results show that participants who were diagnosed with early manifest glaucoma reported lower perceived vection strength and spatial presence compared with healthy participants. In contradistinction, participants who were diagnosed with AMD experience higher perceived vection strength and spatial presence compared with healthy participants. Both AMD and glaucoma groups reported reduced severity in cybersickness compared to healthy normals.

Our results demonstrated significant effects in self-motion perception despite having near normal visual acuities or visual fields. Our results support previous studies which found that self-motion perception is either similar[40] or enhanced[41] in those with bilateral central vision loss compared with normal vision. Our participants have earlier presentations of AMD where marked central vision loss was not observed. It is postulated that those with AMD are more sensitive to their peripheral vision because of compensation of the deficit in their central visual field. This highlights that there may be early functional changes within the retina that would otherwise be missed as a result of conventional testing. This further highlights an issue in current standard clinical assessment whereby patients are potentially missed for having visual problems. This encourages a more holistic approach in visual assessment to ensure patients with eye disease are receiving the best management.[65]

On the contrary, those with early manifest glaucoma reported a reduction in perceived vection strength. Previous studies have demonstrated preferential damage to the magnocellular pathway in glaucoma.[66] Because motion perception is predominantly mediated by the magnocellular pathway, this leads us to believe that motion perception is impaired in patients with glaucoma. Traditionally, visual function in patients with glaucoma have been described as "peripheral vision loss." This occurs in the form of scotomata in the periphery, whereby, patients would have "black spots" in their vision forming tunnel vision. Recent studies have demonstrated that visual perception is not what was first thought and appears to the patient more like "blur," "grayed out," "white," or "cloudiness" patches.[67–69] Interestingly, visual field deficits in glaucoma are not limited to the periphery, but rather also affect the central visual field as well.[70] Zhang et al.[71] explored the effects of reduced contrast and field of view on object motion and self-motion. They reported that reduced contrast affects the perception of object motion but not of self-motion, whereas field of view affects the perception of self-motion and not object motion. The combination of central and peripheral field changes, as well as changes in contrast may reduce retinal stimulation and hence impair perceived self-motion in depth. This further suggests that perhaps our methods of conventional clinical testing should be reassessed and improved on for earlier detection of functional deficits.

The present study found that perceived spatial presence was relatively enhanced in the AMD group and similar or relatively reduced in the glaucoma group compared with healthy normals. This may be explained by our ability to perceive a 3D environment by using ambient spatial processing in the peripheral vision.[72] It is thought that those with AMD may experience a higher level of immersion within a 3D space as their peripheral vision remains intact. As ambient processing relies on the magnocellular pathway, this may explain why those with glaucoma perceive reduced spatial presence. We also found a positive relationship between the experience of spatial presence and the percept of self-motion in depth across all groups. These findings are consistent with previous studies that have reported a similar positive relationship.[73,74] This may also account for the differences observed in the percept of self-motion in depth between groups.

We found that symptoms of cybersickness were similar across all simulated speeds. These findings support Palmisano et al.[37] who found that there was no significant relationship between vection and cybersickness. Interestingly, we also found no significant relationship between spatial presence and cybersickness. Our participants typically reported either no cybersickness at all (Fast Motion Sickness score of 0 out of 20) or relatively weak cybersickness ratings if they did develop symptoms. Participants also found it difficult to judge whether mild symptoms were indicative of actual cybersickness. One possible trigger for cybersickness is visual-vestibular/visual-nonvisual sensory conflict. The visual scene on our retinas are thought to be stabilized by automated eye movements during head movement.[75] The display within an HMD is generated by factoring in head displacement through the use of in-built head tracking technologies. System limitations such as system lag or calibration errors could result in inconsistencies in the visual and inertial information leading to sensory conflict. Even at low latencies of lag (<5 ms), which are achievable on recent Oculus Rift HMD models, mild symptoms of cybersickness were still reported.[49]

There was also a trend for viewing condition to impact both perceived vection and spatial presence across all groups. As previously mentioned, there may be a hypersensitivity in the peripheral visual field in those with AMD because of a central visual field deficit. This, in addition to sensory integration, may further enhance perceived vection. Similarly, if we account for the role of peripheral visual fields in both vection and spatial presence, then any peripheral visual field loss, leading to reduced sensory input and sensory mismatches, would disadvantage those with glaucoma in experiencing vection and spatial presence. These findings highlight that those with different eye conditions may experience varied sensory conflict and, hence, have altered perceptual experiences. Furthermore, we found that the passive versus active viewing conditions only had a significant impact on cybersickness. This supports the above sensory conflict theory that sensory mismatch will generate more symptoms of cybersickness, as viewing conditions were manipulated to vary sensory conflict (or sensory integration).

Participants with AMD or glaucoma reported relatively lower severity in symptoms of cybersickness compared with normal participants. Cybersickness was more likely to be experienced after active head movements without

Investigative Ophthalmology & Visual Science

ecological compensation (active pure radial) and the difference between AMD and glaucoma and normals was greatest in this viewing condition. It has been documented that the severity of glaucoma[45] and AMD[46] may progress in one eye more than the other. This may lead to an imbalance of retinal stimulation and reduced binocular vision such as stereopsis, despite being fully corrected for refractive error. This finding also supports a recent report that found that monocular viewing reduces cybersickness severity.[48] The increased severity of cybersickness during binocular conditions may be explained by sensory conflict caused by display artefacts that are generated and only visible during binocular viewing. This may be an inherent issue secondary to the asynchronous time warp used by Oculus that is designed to reduce the display rendering times following head movements.[48]

In conclusion, we have demonstrated that self-motion perception is differentially biased in patients with early eye disease. HMDs offer great utility to better understand motion processing in virtual environments for those with early eye disease impacting their central and peripheral visual fields. This is the first study to investigate the effects of two leading causes of irreversible blindness on the perception of linear self-motion in HMD virtual environments. It would be of benefit in the future to ascertain the extent to which other types and severity of ocular disorders disrupt the sensation of retinal motion and bias perception of self-motion in the real world.

Acknowledgments

The authors thank J. Feng and N. Chowdury for technical assistance.

Supported by the Sensory Processes Innovation Network (SPINet) and a travel award for WL to present the findings at the 2019 Asia Pacific Conference on Vision (APCV'19). W.L. is a PhD candidate supported by the Australian Government Research Training Program and a scholarship from Guide Dogs NSW/ACT. B.Z. and M.K. receive salary support from Guide Dogs NSW/ACT. J.K. was supported by an ARC Future Fellowship (FT140100535).

Disclosure: **W. Luu,** None; **B. Zangerl,** None; **M. Kalloniatis,** None; **S. Palmisano,** None; **J. Kim,** None

References

1. Mitchell P, Smith W, Attebo K, Wang JJ. Prevalence of age-related maculopathy in Australia. The Blue Mountains Eye Study. *Ophthalmology*. 1995;102(10):1450–1460.
2. Keel S, Xie J, Foreman J, Lee PY, Alwan M, Fahy ET, et al. Prevalence of glaucoma in the Australian National Eye Health Survey. *Br J Ophthalmol*. 2019;103(2):191–195.
3. Quigley HA, Broman AT. The number of people with glaucoma worldwide in 2010 and 2020. *Br J Ophthalmol*. 2006;90(3):262–267.
4. De Moraes CG, Liebmann JM, Levin LA. Detection and measurement of clinically meaningful visual field progression in clinical trials for glaucoma. *Prog Retin Eye Res*. 2017;56:107–147.
5. Aizawa N, Kunikata H, Shiga Y, Tsuda S, Yokoyama Y, Omodaka K, et al. Preperimetric Glaucoma Prospective Observational Study (PPGPS): Design, baseline characteristics, and therapeutic effect of tafluprost in preperimetric glaucoma eye. *PLoS One*. 2017;12(12):e0188692.
6. Casson RJ, Chidlow G, Wood JP, Crowston JG, Goldberg I. Definition of glaucoma: clinical and experimental concepts. *Clin Exp Ophthalmol*. 2012;40(4):341–349.
7. Mitchell P, Smith W, Attebo K, Healey PR. Prevalence of open-angle glaucoma in Australia. The Blue Mountains Eye Study. *Ophthalmology*. 1996;103(10):1661–1669.
8. Wong EY, Keeffe JE, Rait JL, Vu HT, Le A, McCarty Ph DC, et al. Detection of undiagnosed glaucoma by eye health professionals. *Ophthalmology*. 2004;111(8):1508–1514.
9. Shabana N, Cornilleau Peres V, Carkeet A, Chew PT. Motion perception in glaucoma patients: a review. *Surv Ophthalmol*. 2003;48(1):92–106.
10. Bullimore MA, Wood JM, Swenson K. Motion perception in glaucoma. *Invest Ophthalmol Vis Sci*. 1993;34(13):3526–3533.
11. Gibson JJ. *The Perception of the Visual World*. Boston: Houghton-Mifflin; 1950.
12. Palmisano S, Allison RS, Schira MM, Barry RJ. Future challenges for vection research: definitions, functional significance, measures, and neural bases. *Front Psychol*. 2015;6:193.
13. Dichgans J, Brandt T. Visual-Vestibular Interaction: Effects on Self-Motion Perception and Postural Control. In: Held R, Leibowitz HW, Teuber HL , eds. *Perception. Handbook of Sensory Physiology. 8*. Berlin, Heidelberg: Springer; 1978:755–804.
14. Kim J, Khuu S. A new spin on vection in depth. *J Vis*. 2014;14(5):5.
15. Seno T, Murata K, Fujii Y, Kanaya H, Ogawa M, Tokunaga K, et al. Vection Is Enhanced by Increased Exposure to Optic Flow. *Iperception*. 2018;9(3):2041669518774069.
16. Fujii Y, Seno T. The Effect of Optical Flow Motion Direction on Vection Strength. *Iperception*. 2020;11(1):2041669519899108.
17. Andersen GJ, Braunstein ML. Induced self-motion in central vision. *J Exp Psychol Hum Percept Perform*. 1985;11(2):122–132.
18. Palmisano S, Allison RS, Ash A, Nakamura S, Apthorp D. Evidence against an ecological explanation of the jitter advantage for vection. *Front Psychol*. 2014;5:1297.
19. Palmisano S, Allison RS, Kim J, Bonato F. Simulated viewpoint jitter shakes sensory conflict accounts of vection. *Seeing Perceiving*. 2011;24(2):173–200.
20. Kim J, Palmisano S. Eccentric gaze dynamics enhance vection in depth. *J Vis*. 2010;10(12):7.
21. Kim J, Tran MT. A New Angle on Object-Background Effects in Vection. *Iperception*. 2016;7(2):2041669516631695.
22. Palmisano S, Kim J, Freeman TC. Horizontal fixation point oscillation and simulated viewpoint oscillation both increase vection in depth. *J Vis*. 2012;12(12):15.
23. Nakamura S, Palmisano S, Kim J. Relative visual oscillation can facilitate visually induced self-motion perception. *Iperception*. 2016;7(4):2041669516661903.
24. Nakamura S. Effects of additional visual oscillation on vection under voluntary eye movement conditions–retinal image motion is critical in vection facilitation. *Perception*. 2013;42(5):529–536.
25. Mohler BJ, Thompson WB, Creem-Regehr SH, Pick HL, Jr., Warren WH, Jr. Visual flow influences gait transition speed and preferred walking speed. *Exp Brain Res*. 2007;181(2):221–228.
26. Bossard M, Goulon C, Mestre DR. Viewpoint oscillation improves the perception of distance travelled based on optic flow. *J Vis*. 2016;16(15):4.
27. Bossard M, Mestre DR. The relative contributions of various viewpoint oscillation frequencies to the perception of distance traveled. *J Vis*. 2018;18(2):3.

28. Brandt T, Dichgans J, Koenig E. Differential effects of central verses peripheral vision on egocentric and exocentric motion perception. *Exp Brain Res*. 1973;16(5):476–491.
29. Keshavarz B, Speck M, Haycock B, Berti S. Effect of different display types on vection and its interaction with motion direction and field dependence. *Iperception*. 2017;8(3):2041669517707768.
30. Palmisano S, Gillam B. Stimulus eccentricity and spatial frequency interact to determine circular vection. *Perception*. 1998;27(9):1067–1077.
31. Post RB. Circular vection is independent of stimulus eccentricity. *Perception*. 1988;17(6):737–744.
32. Nakamura S, Shimojo S. Stimulus size and eccentricity in visually induced perception of horizontally translational self-motion. *Percept Mot Skills*. 1998;87(2):659–663.
33. Tarita-Nistor L, Gonzalez EG, Spigelman AJ, Steinbach MJ. Linear vection as a function of stimulus eccentricity, visual angle, and fixation. *J Vestib Res*. 2006;16(6):265–272.
34. Novák-Marcinčin J. Hardware devices used in virtual reality technologies. *Scientific Bulletin Series C: Fascicle Mechanics, Tribology, Machine Manufacturing Technology*. 2010;24:57.
35. Sherman WR, Craig AB. *Understanding Virtual Reality - Interface, Application, and Design*. San Francisco: Morgan Kaufmann; 2002:608.
36. Kim J, Chung CY, Nakamura S, Palmisano S, Khuu SK. The Oculus Rift: a cost-effective tool for studying visual-vestibular interactions in self-motion perception. *Front Psychol*. 2015;6:248.
37. Palmisano S, Mursic R, Kim J. Vection and cybersickness generated by head-and-display motion in the Oculus Rift. *Displays*. 2017;46(2017):1–8.
38. Riecke BE, Jordan JD. Comparing the effectiveness of different displays in enhancing illusions of self-movement (vection). *Front Psychol*. 2015;6:713.
39. Palmisano S, Riecke BE. The search for instantaneous vection: An oscillating visual prime reduces vection onset latency. *PLoS One*. 2018;13(5):e0195886.
40. Shanidze N, Verghese P. Motion perception in central field loss. *J Vis*. 2019;19(14):20.
41. Tarita-Nistor L, Gonzalez EG, Markowitz SN, Lillakas L, Steinbach MJ. Increased role of peripheral vision in self-induced motion in patients with age-related macular degeneration. *Invest Ophthalmol Vis Sci*. 2008;49(7):3253–3258.
42. Brin TA, Tarita-Nistor L, Gonzalez EG, Trope GE, Steinbach MJ. Vection responses in patients with early glaucoma. *J Glaucoma*. 2019;28(1):68–74.
43. Skarbez R, Brooks Jr FP, Whitton MC. Immersion and coherence in a stressful virtual environment. *24th ACM Symposium on Virtual Reality Software and Technology*; Tokyo, Japan. New York: ACM, New York, USA; 2018. p. 11.
44. Riener R, Harders M. *Virtual Reality in Medicine*. London: Springer-Verlag; 2012.
45. Kingdon KS, Stanney KM, Kennedy RS, editors. Extreme responses to virtual environment exposure. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*; 2001: Los Angeles: SAGE Publications Sage CA.
46. Reason JT, Brand JJ. *Motion sickness*. Cambridge, MA: Academic Press; 1975.
47. Reason JT. Motion sickness adaptation: a neural mismatch model. *J R Soc Med*. 1978;71(11):819–829.
48. Palmisano S, Szalla L, Kim J. Monocular viewing protects against cybersickness produced by head movements in the oculus rift. In: Trescak T, Simoff S, Richards D, Bogdanovych A, Duval T, Khulen T, et al., eds. *VRST '19: 25th ACM Symposium on Virtual Reality Software and Technology; November 12-15*; Parramatta: Association for Computing Machinery; 2019:1–2.
49. Feng J, Kim J, Luu W, Palmisano S. *Method for estimating display lag in the Oculus Rift S and CV1. SIGGRAPH Asia 2019*; Brisbane, Australia: Association for Computing Machinery; 2019:39.
50. Kim J, Luu W, Palmisano S. Multisensory integration and the experience of scene instability, presence and cybersickness in virtual environments. *Comp Hum Behav*. 2020;113:106484.
51. Meehan M, Razzaque S, Whitton M, Brooks F, eds. Effects of latency on presence in stressful virtual environments. *Proceedings of IEEE Virtual Reality 2003*; 2003; Los Angeles: IEEE Computer Society.
52. Heeter C. Being there: the subjective experience of presence. *Presence: Teleoperators & Virtual Environments*. 1992;1(2):262–271.
53. Cooper N, Milella F, Pinto C, Cant I, White M, Meyer G. The effects of substitute multisensory feedback on task performance and the sense of presence in a virtual reality environment. *PLoS One*. 2018;13(2):e0191846.
54. Kim J, Palmisano S. Effects of active and passive viewpoint jitter on vection in depth. *Brain Res Bull*. 2008;77(6):335–342.
55. Zacharias GL, Young LR. Influence of combined visual and vestibular cues on human perception and control of horizontal rotation. *Exp Brain Res*. 1981;41(2):159–171.
56. Kim J, Moroz M, Arcioni B, Palmisano S. Effects of head-display lag on presence in the oculus rift. *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*; Tokyo: Association for Computing Machinery; 2018. p. Article 83.
57. Ferris FL, 3rd, Wilkinson CP, Bird A, et al. Clinical classification of age-related macular degeneration. *Ophthalmology*. 2013;120(4):844–851.
58. Ly A, Wong E, Huang J, Yapp M, Masselos K, Hennessy M, et al. Glaucoma community care: Does ongoing shared care work? *Int J Integr Care*. 2020;20(3):5.
59. Ly A, Yapp M, Nivison-Smith L, Assaad N, Hennessy M, Kalloniatis M. Developing prognostic biomarkers in intermediate age-related macular degeneration: their clinical use in predicting progression. *Clin Exp Optom*. 2018;101(2):172–181.
60. Mills RP, Budenz DL, Lee PP, Noecker RJ, Walt JG, Siegartel LR, et al. Categorizing the stage of glaucoma from pre-diagnosis to end-stage disease. *Am J Ophthalmol*. 2006;141(1):24–30.
61. Bouchard S, Robillard G, St-Jacques J, Dumoulin S, Patry M, Renaud P. Reliability and validity of a single-item measure of presence in VR. *The 3rd IEEE International Workshop on Haptic, Audio and Visual Environments and Their Applications*. 2004:59–61.
62. Clifton J, Palmisano S. Effects of steering locomotion and teleporting on cybersickness and presence in HMD-based virtual reality. *Virtual Reality*. 2019;24(3):453–468
63. Keshavarz B, Hecht H. Validating an efficient method to quantify motion sickness. *Hum Factors*. 2011;53(4):415–426.
64. Anderson AJ, Vingrys AJ. Small samples: does size matter? *Invest Ophthalmol Vis Sci*. 2001;42(7):1411–1413.
65. Luu W, Kalloniatis M, Bartley E, Tu M, Dillon L, Zangerl B, et al. A holistic model of low vision care for improving vision-related quality of life. *Clin Exp Optom*. 2020;103(6):733–741.
66. Ansari EA, Morgan JE, Snowden RJ. Psychophysical characterisation of early functional loss in glaucoma and ocular hypertension. *Br J Ophthalmol*. 2002;86(10):1131–1135.
67. Crabb DP, Smith ND, Glen FC, Burton R, DF Garway-Heath. How does glaucoma look?: patient perception of visual field loss. *Ophthalmology*. 2013;120(6):1120–1126.

Investigative Ophthalmology & Visual Science

68. Hu CX, Zangalli C, Hsieh M, Gupta L, Williams AL, Richman J, et al. What do patients with glaucoma see? Visual symptoms reported by patients with glaucoma. *Am J Med Sci*. 2014;348(5):403–409.
69. Fujitani K, Su D, Ghassibi MP, Simonson JL, Liebmann JM, Ritch R, et al. Assessment of patient perception of glaucomatous visual field loss and its association with disease severity using Amsler grid. *PLoS One*. 2017;12(9):e0184230.
70. Kim JM, Kyung H, Shim SH, Azarbod P, Caprioli J. Location of initial visual field defects in glaucoma and their modes of deterioration. *Invest Ophthalmol Vis Sci*. 2015;56(13):7956–7962.
71. Zhang X, Lawrence JJ, Nalbandian AT, Owens DA. Differential effects of contrast and field size on the perception of object-motion and self-motion: new evidence for ambient and focal modes of vision. *J Vis*. 2010;10(15):36.
72. Rooney KK, Condia RJ, Loschky LC. Focal and ambient processing of built environments: intellectual and atmospheric experiences of architecture. *Front Psychol*. 2017;8:326.
73. Weech S, Kenny S, Barnett-Cowan M. Presence and cybersickness in virtual reality are negatively related: a review. *Front Psychol*. 2019;10:158.
74. Keshavarz B, Philipp-Muller AE, Hemmerich W, Riecke BE, Campos JL. The effect of visual motion stimulus characteristics on vection and visually induced motion sickness. *Displays*. 2019;58:71–81.
75. Durant S, Zanker JM. The combined effect of eye movements improve head centred local motion information during walking. *PLoS One*. 2020;15(1):e0228345.

Investigative Ophthalmology & Visual Science