The Effect of Retinal Eccentricity on Visually Induced Motion Sickness and Postural Control

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Abstract: The present study investigated the effect of retinal eccentricity on visually induced motion sickness (VIMS) and postural control. Participants wore a head-mounted display masked for the central 10° (peripheral vision), the peripheral except for the central 10° (central vision), or unmasked (control) to watch a highly immersive 3D virtual reality (VR) ride along China’s Great Wall. The Simulator Sickness Questionnaire was administered to assess VIMS symptoms before and after the VR exposure. In addition, postural sway data were collected via sensors attached to each participant’s head, torso, and hip. Results demonstrated that peripheral vision triggered the most severe symptoms of motion sickness, whereas full vision most perturbed posture. The latter finding contradicts previous research findings demonstrating the peripheral advantage of postural control. Although the source of compromised postural control under peripheral stimulation is not clear, the provocative nature of visual stimulation depicting a roller-coaster ride along a rugged path likely contributed to the contradictory findings. In contrast, motion sickness symptoms were least severe, and posture was most stable, under central vision. These findings provide empirical support for the tactic assumed by VR engineers who reduce the size of the field of view to ameliorate the symptoms of motion sickness.

Keywords: virtual reality; visually induced motion sickness; retinal eccentricity; head mounted display; simulation sickness questionnaire; postural control

1. Introduction

The term “vection” refers to the illusory sensations of self-motion in the absence of actual observer movement [1,2] (see [3] for an overview). It is these illusions that are taken advantage of in virtual reality (VR), wherein users interact with an artificially created environment. Recent advancements in VR technology, driven primarily by the game industry, further blur the boundary between the virtual and the real. At the center of the technological advancements are head-mounted displays (HMD). Equipped with the capacity to track the motion of the user’s head and deliver images in 3-dimensions (3D), these devices convey a compelling sense of immersion in the virtual environment.

However, for some users, VR also can trigger drowsiness, dizziness, fatigue, pallor, sweating, stomach awareness, nausea, and disorientation akin to the symptoms commonly experienced by people reporting motion sickness. When experienced during exposure to VR, these symptoms are generally referred to as visually induced motion sickness (VIMS) (see [4] for an overview). Because visual inputs are unaccompanied by the corresponding vestibular and somatosensory inputs during VR exposure, the central nervous system receives incongruent information from different sensory channels. Sensory conflict theory contends that it is the contradictory information across various sensory channels that causes VIMS [5,6]. Other researchers contend that the role of information lies, neither in its processing nor in its content alone, but in the service of action to accomplish an intended goal. Simultaneously, the action system explores the surrounding environment in search of requisite
information to facilitate attaining an intended goal [7,8]. In this way, perception and action are coupled, thus forming a continuous loop, an insight attributed to J.J. Gibson. In this view, the visual information depicted on the HMD specifies a behavior different from that in which the (stationary) user wearing the HMD is engaged. In other words, the mismatch that arises in VR is not between information from different channels, but between the behavior specified by the depicted visual pattern and the current behavior the user is executing. Consider a user experiencing VR via an HMD while standing. Even when standing still, the VR user’s body sways, engendering optical flow, which in turn is utilized in conjunction with the information from vestibular and proprioceptive receptors to maintain balance. The visual pattern depicted on the HMD, however, specifies illusory movement through a virtual environment, which would necessitate a very different behavior from that needed to maintain an upright stance. For certain people, the coupling between perception and action is now compromised, making the task of maintaining posture more challenging than if based on the veridical information available in the real world. Such degraded capacity to control posture is what triggers VIMS in VR and is the central tenet underlying postural instability theory [9–11]. Sensory conflict theory and postural instability theory are two prominent theories put forth to account for VIMS. Both recognize informational conflict inherent in VR as the source of VIMS, but the postural instability theory goes further to underscore the consequences of information detected on behavior, in general, and on postural control in particular.

With an uneven distribution of neural receptors across its surface, the retina is thought to be divided into two distinct regions, center and periphery, whose functional roles differ. Indeed, numerous studies have been conducted to elucidate the center-periphery distinction in visual perception. Dichgans and colleagues first addressed this issue by using circular vection or rotary self-motion perception [12–14]. Brandt et al. [12] reported that stimulating the peripheral retina, particularly outside a 30° diameter area of the central visual field, can elicit self-motion perception, but stimulating the central retina cannot. The researchers concluded that the central retina is dominant in object recognition and identification and the peripheral retina is dominant in visually induced self-motion and spatial orientation. The results of subsequent research, however, were mixed—and sometimes contradictory. Nevertheless, the majority of studies confirmed the findings of Dichgans and colleagues (see [15] for an overview). Moreover, the intensity of vection was shown to be enhanced with a wider field of view, thus reinforcing the peripheral efficacy for vection [12,16].

The widening of the field of view, in effect, expands the area of the retinal periphery that can be stimulated. The question can be raised, then, as to the effect of the increased stimulation in the retinal periphery on VIMS. Now that a variety of low-cost HMDs are available on the consumer market, this issue is particularly relevant. Equipped with high resolution and wide fields of view displays, these devices can convey a compelling sense of immersion in the virtual environment. The information depicted on an HMD describes the transformation of the entire scene, thus provoking an illusion of observer movement, that is, vection, which is assumed to be the prerequisite for VIMS [1–3,17]. As the field of view provided by these devices becomes wider, the more effectively they convey vection, along with a concurrent increase in the incidence of motion sickness [1,15]. Indeed, VR engineers have manipulated the size of the visual field in an attempt to reduce motion sickness symptoms based on the general assumption that a wider field of view tends to aggravate sickness symptoms [18–20].

Research exploring the relationship between visual field and postural control has also demonstrated that the retinal periphery plays the dominant role in stabilizing posture, particularly in the anterior-posterior (AP) direction [12,21–26] (see [27] for review). In these studies, body sway was less with peripheral stimulation than with central stimulation [22,23,28].

Taken together, these findings suggest that the retinal periphery is more effective for inducing vection and for stabilizing posture. However, when considering VIMS, the findings are contradictory. VIMS is more likely to occur with vection [1–3,17] but less likely to occur with stable posture. The differing relationships of VIMS with vection and posture have been confirmed repeatedly. For example, extensive research by postural instability theory proponents at different laboratories has
demonstrated convincingly that postural instability is the precursor to VIMS [10,29–32]. How can we reconcile these contradictory findings?

One possible way to clarify the seemingly contradictory findings is to manipulate the complexity of visual motion used to produce vection. Most studies reporting stable posture under peripheral stimulation induced vection simulating locomotion along a single axis, e.g., a collection of random dots that moved from left to right (i.e., linear vection [25,26]), remained stationary [22,23], or a drum that rotated about the vertical axis against a wall painted in black and white vertical stripes (circular vection, [12]) (see [27] for review). Although the intensity of the vection strength participants of these studies experienced is unclear, these visual motions may not adequately capture the dynamic nature of visual effects rendered in most VR applications.

The present study investigated the effect of retinal eccentricity on VIMS and postural control in an immersive VR environment to determine whether the retinal periphery is still dominant even under more provocative visual stimulation. As noted earlier, VR engineers reduce the size of the field of view to ameliorate the symptoms of motion sickness [18–20]. We expected, therefore, that stimulation of a wider area of the retinal periphery with visual patterns engendered by more complex movement geometry, that is, forward translation along a bumpy path simulating a roller-coast ride, should be more detrimental to posture and therefore elicit more severe symptoms of motion sickness than stimulation of the central retina, a finding that could justify VR engineers’ solution to reduce motion sickness.

2. Materials and Methods

Participants. Thirty-six participants, all undergraduates and graduates from Keimyung University, volunteered for the experiment. All participants had normal or corrected-to-normal vision, with no previous history of postural or vestibular dysfunction. Participants were randomly assigned to one of three experimental groups (central vision, peripheral vision, or full vision). Participants in the full vision group served as controls. Each group was comprised of 12 participants (6 males and 6 females). Participants were asked to refrain from eating for a minimum of three hours prior to the experiment. The study was approved by the Keimyung University’s Institutional Review Board, and written informed consent was obtained from participants prior to their participation.

Stimulus. Participants watched The Great Wall (Niceberg Studios, Belgium). This VR application conveyed a first-person perspective of a rocket powered rickshaw ride over The Great Wall of China in a highly immersive stereoscopic 3D environment. The VR ride took 4.17 min.

Apparatus. A Samsung Gear VR (SM-R324, Samsung, Suwon, Korea) headset and a Samsung Galaxy S8 smartphone (Samsung, Suwon, Korea) which acted as the headset’s display and processor were used to present the VR exposure. S8 is equipped with a 5.8 inch display panel. The display had a refresh rate of 60 Hz and a pixel resolution of 1280 H × 1440 V per eye, which yielded a 101° horizontal field of view. Head-tracking was enabled, providing a 360° field of view. In the central vision condition, each eye’s view was masked except for the central 10° while, in the peripheral vision condition, the central 10° of each eye’s view was masked. The control group viewed the display via an unmasked HMD.

A Polhemus G4 (Polhemus, Colchester, VT, USA) wireless motion tracking system was used to record the postural sway of participants. Three sensors were attached to each participant’s head, cervical spine (C7–T1 junction), and base of the spine (lumbo–sacral junction) to collect the six degrees of freedom position data at 120 Hz.

VIMS symptoms were assessed using the Simulator Sickness Questionnaire (SSQ) [33]. The 16-item questionnaire rates symptom intensities on a four-point scale (0 = none, 1 = slight, 2 = moderate, or 3 = severe). The SSQ scores are grouped under three subscales (nausea, oculomotor distress, and disorientation), yielding four scores: three sub-scores and a total score that serves as an indicator of overall severity of the simulator sickness. The SSQ was administered at the beginning and end of the experiment. The pre-exposure administration was to familiarize participants with the
symptoms of VIMS and to provide a baseline level of symptoms for comparison with the scores from post-exposure administration.

**Procedure.** After completing the informed consent procedure, participants filled out the pre-exposure SSQ. After donning the Gear VR, participants were allowed to explore the virtual environment briefly while standing comfortably. With head tracking enabled, the HMD provided a 360° field of view. However, head movements during VR exposure have been found to increase the likelihood of VIMS [2,31]. Thus, to avoid having their head movements provoke or aggravate VIMS, participants were advised to keep their heads still and look directly at the center of the display during the VR ride. Upon termination of the VR ride, participants completed the post-exposure SSQ.

**Data analysis.** Each SSQ administration yielded, for each participant, four scores consisting of one total and three subscale scores obtained using methods and weighting factors as described by [33]. Each set of scores was combined by subtracting the pre-SSQ score from the post-SSQ score, and the combined score was subjected to a Kruskal–Wallis test to assess differences among the three groups.

Body sway data collected from each sensor were evaluated by the standard deviation (SD) of position, velocity, and range of motion, with each measure assessed in both AP and medio-lateral (ML) axes (e.g., [32]). Velocity was obtained by dividing the total length by the sampled duration, and range was defined in terms of the distance between the farthest points of sensor displacement. These parameters were extracted from 4 minutes of data after discarding the first 10 sec. These data were deleted from analysis as a precautionary measure to prevent possible contamination of postural data by tracking system noise or participants’ inadvertent movements at the beginning of the trial. A separate one-way analysis of variance (ANOVA) was performed on each of these parameters with group as the between-subjects factor. The Levene’s test of homogeneity of variance verified that all the dependent measures satisfied the assumptions of homogeneity.

3. Results

3.1. Visually Induced Motion Sickness (VIMS)

Mean weighted SSQ scores for the three groups are presented in Figure 1. The Kruskal–Wallis tests demonstrated statistically significant main effects of group for total score, $H = 8.57$ (2, $N = 36$), $p < 0.05$, nausea, $H = 6.16$ (2, $N = 36$), $p < 0.05$, disorientation, $H = 8.64$ (2, $N = 36$), $p < 0.05$, and a marginally significant effect for oculomotor distress, $H = 5.12$ (2, $N = 36$), $p = 0.08$. Post hoc tests confirmed the differences between peripheral and central vision groups for total score, nausea, and disorientation at the 0.05 significance level.

![Figure 1. Mean weighted Simulator Sickness Questionnaire (SSQ) scores (with standard error bars) for three experimental groups.](image-url)
3.2. Postural Sway

Movement data from the head, torso, and hip are presented in Figure 2 as SD (top panel), velocity (middle panel), and range (bottom panel) in the AP (left panel) and ML (right panel) axes, respectively. In general, postural sway was exaggerated in both peripheral and control groups. The ANOVAs confirmed the main effects of group for several parameters, but only in the AP axis. A significant group effect for SD was confirmed for torso movement, $F(2, 33) = 4.89, p < 0.05, \eta^2_p = 0.23$. For velocity, head, $F(2, 33) = 0.364, p < 0.05, \eta^2_p = 0.18$, torso, $F(2, 33) = 9.75, p < 0.001, \eta^2_p = 0.37$, and hip movements, $F(2, 33) = 6.50, p < 0.01, \eta^2_p = 0.28$, were all statistically significant. For range, torso, $F(2, 33) = 4.27, p < 0.05, \eta^2_p = 0.21$, and hip movements, $F(2, 33) = 4.67, p < 0.05, \eta^2_p = 0.22$, were statistically significant. Tukey post hoc tests showed that the differences between the central vision and control groups contributed to the significant effects for all measures except for velocity of hip movement where both peripheral vision and control groups differed from the central vision group.

![Figure 2](image-url)

Figure 2. Movement data from the head, torso and hip as standard deviation (SD) (top panel), velocity (middle panel), and range (bottom panel) in the anterior-posterior (AP) (left panel) and medio-lateral (ML) (right panel) axes for three experimental groups. Error bars represent ±1 SE of the mean. * $p < 0.05$.
4. Discussion

The present study attempted to elucidate the seemingly conflicting findings reported in the literature on the relationship between retinal eccentricity, VIMS, and postural control. In particular, we sought to clarify (in a more dynamic VR environment) whether peripheral stimulation produces, not only more severe symptoms of motion sickness, but also more unstable posture than central stimulation. Wearing an HMD masked for the central 10° (peripheral vision), the peripheral except for the central 10° (central vision), or unmasked (control), participants watched The Great Wall, a 3D VR application conveying self-movement along China’s Great Wall while in a rocket-powered rickshaw. SSQ was administered to assess VIMS symptoms before and after VR exposure. In addition, postural sway data were collected using a wireless motion tracking system with sensors attached to participants’ heads, torsos, and hips.

Although no participant reported any symptoms prior to the experiment (pre-SSQ scores for the three groups were 1.87 (peripheral vision), 0.94 (central vision), and 2.18 (control), respectively), all three experimental conditions produced and/or enhanced motion sickness symptoms after VR exposure. Peripheral vision provoked the most severe motion sickness symptoms, not only in the total score, but also in the three SSQ sub-scores (Figure 1). In contrast, full vision (the control condition) most perturbed posture, particularly in the AP direction (Figure 2). The effects of VR exposure were weakest for both subjective assessment of motion sickness and postural disturbance under central vision.

Finding that the retinal periphery enhances motion sickness symptoms is consistent with the general consensus held in the VR community [18–20] wherein its practitioners reduce the field of view in an attempt to lessen motion sickness symptoms. In the current study, reported symptom severity was greater with full vision than central vision. Because the retinal periphery was stimulated in both peripheral vision and full vision conditions, it appears that the retinal periphery is more susceptible to VIMS. This result corroborates the contention that the retinal periphery facilitates vection [12,13,34] and that vection is a prerequisite for VIMS [1,10].

Postural sway increased more with full vision than with peripheral vision. Central vision induced the least disturbance, particularly in the AP direction. Raffi and Piras [27], in their critical review investigating the relationship of field of view and postural control, confirmed that the majority of the 12 studies identified peripheral vision as dominant in postural control, stabilizing posture when individuals are subjected to vection. This conclusion was true irrespective of the various sizes of central and peripheral visual fields defined in the studies, and also irrespective of the different hardware systems employed to produce vection (e.g., desktop display, projection screen, HMD), and more. Given this robust finding, we suspected that the peripheral advantage of postural control reported in the literature may have been due to the use of relatively simple visual patterns (e.g., linear translation, circular rotation, or random dots that remained stationary) to induce vection. Although it is not clear how the retinal periphery resolves the informational conflict inherent in vection illusions to effect postural control, this ability is no longer preserved under more complex visual stimulation.

It may be that increased conflict of information from different sensory channels produced the current results. In our study, participants standing upright experienced vection depicting two-dimensional motion (i.e., forward locomotion along a rugged path). Palmisano and colleagues increased sensory conflict in their radial optic flow displays by adding jitter, i.e., viewpoint oscillation [35,36] (see [37] for an overview). This manipulation produced more motion sickness symptoms than non-oscillating radial optic flow, but, more importantly, enhanced vection, resulting in mixed results, with the former corroborating, but the latter contradicting, what might be predicted by the sensory conflict theory. The manipulation’s effect on postural control was also mixed, with posture being disturbed in the posterior direction but not in the anterior direction. The researchers found sensory conflict theory inadequate to account for all their findings. Similarly, (the degree of) informational conflict should be ruled out as the source of postural instability under peripheral stimulation, as observed here. Irrespective of the etiology of the present finding, it appears that the peripheral advantage of postural control is no longer maintained under more complex and dynamic visual stimulation.
However, the present findings are consistent with the predictions of postural instability theory, that is, unstable posture under peripheral stimulation leading to increased motion sickness symptoms.

It is important to recognize how effective the central retina was, not only in reducing the symptoms of motion sickness, but also in stabilizing posture. These findings provide sound evidence for the strategy employed by VR engineers to cope with increasing reports of motion sickness associated with VR.

Participants in the current study reported that they experienced the most severe motion sickness symptoms in the peripheral vision condition, but their body swayed most under full vision (the control condition), resulting in a discrepancy between subjective ratings of motion sickness symptoms and the extent of postural perturbation. The severity of symptoms reported under the central vision and full vision conditions was indistinguishable. These results are inconsistent with what postural instability theory would predict. In the present study, VR exposure lasted only 4.17 min, a relatively short duration. This effect, taken together with the previous finding that HMDs are nauseogenic [29,38,39], may have contributed to this discrepant result (see also [2]). Motion sickness is known to be subject to large individual differences [1,30,40]. These individual differences might have confounded the between-subject design employed in the present study. With random assignment of participants to one of the three experimental groups, the possibility is negligible, but nonetheless it exists.

Merhi et al. [29] investigated whether playing console video games via an HMD triggers motion sickness. Before analyzing the data, the authors partitioned their participants into sick and well groups. Those who discontinued playing the assigned console video game during the 50 min session, declaring that they were motion sick were allocated to the sick group, whereas those who did not declare motion sickness were allocated to the well group. In their Experiment 2, the data from nine participants qualified for further analysis. Of these nine participants, eight were assigned to the sick group and one was assigned to the well group. Interestingly, the mean total post-SSQ score of the sick group was 77.6 (SD = 25.8), whereas that of the well group was 93.5 (SD = 0). Perhaps this puzzling result can be accounted for by the fact that the SSQ is a subjective measure that assesses the severity of motion sickness symptoms felt by VR users. The same fact may account for the discrepant result observed in the present study. However, further consideration of this result is left for future research.

In the present study we used only one size (10°) to define each visual field condition. Thus, our efforts can be understood only as a preliminary study directed at the relationship between retinal eccentricity, VIMS, and postural control. More systematic variation of the sizes of field of view, as was done by Kim [41], is necessary for a better understanding of the issues addressed in this study. For that reason, caution should be exercised not to overgeneralize the present findings.

5. Conclusions

In conclusion, the present study investigated the effect of retinal eccentricity on VIMS and postural control. Participants were exposed to a highly immersive 3D virtual environment via an HMD equipped with a high resolution, wide field-of-view display. Results demonstrated that peripheral vision triggered most severe symptoms of motion sickness, whereas full vision most perturbed posture. Although the latter finding contradicts previous research findings demonstrating the peripheral advantage of postural control, the findings corroborate postural instability theory, which suggests unstable posture as the source of motion sickness. Although the source of compromised postural control under peripheral stimulation is not clear, the provocative nature of visual stimulation depicting a roller-coaster ride along a rugged path likely contributed to the contradictory finding. Motion sickness symptoms were least severe, and posture was most stable, under central vision. These findings provide empirical support for the tactic assumed by VR practitioners who manipulate the size of the visual field in an attempt to reduce motion sickness symptoms in a virtual environment.
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