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Vection change exacerbates simulator sickness in virtual environments

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Keywords

Vection, change, exacerbates, simulator, sickness, virtual, environments

Disciplines

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Vection Change Exacerbates Simulator Sickness in Virtual Environments

Abstract

The optic flow patterns generated by virtual reality (VR) systems typically produce visually induced experiences of self-motion (vection). While this vection can enhance presence in VR, it is often accompanied by a variant of motion sickness called simulator sickness (SS). However, not all vection experiences are the same. In terms of perceived heading and/or speed, visually simulated self-motion can be either steady or changing. It was hypothesized that changing vection would lead to more SS. Participants viewed an optic flow pattern that either steadily expanded or alternately expanded and contracted. In one experiment, SS was measured pretreatment and after 5 min of viewing using the Simulator Sickness Questionnaire. In a second experiment employing the same stimuli, vection onset and magnitude were measured using a computer-interfaced slide indicator. The steadily expanding flow pattern, compared to the expanding and contracting pattern, led to: 1) significantly less SS, 2) lower subscores for nausea, oculomotor, and disorientation symptoms, 3) more overall vection magnitude, and 4) less changing vection. Collectively, these results suggest that changing vection exacerbates SS.

1 Introduction

Virtual reality (VR) systems often lead to visually induced self-motion perception, or *vection* (Fischer & Kornmüller, 1930; Tschermak, 1931). When vection occurs, the user perceives self-motion that is often compelling even in the absence of any physical self-motion relative to earth. Vection is important in virtual environments because it can enhance the realism, or *presence,* of the user's experience. For example, a flight simulator's visual display may produce vection similar to the self-motion perception that would occur in an actual aircraft, even though the simulator may be stationary relative to earth.

However, vection is often accompanied by a form of kinetosis (motion sickness) known as *simulator sickness* (SS; Kennedy, Hettinger, & Lilienthal, 1989). Symptoms can include, but are not limited to, dizziness, headache, salivation, blurred vision, eyestrain, nausea, disorientation, sweating, and pallor. Often less severe than the more well known forms of kinetosis (seasickness, airsickness, etc.), simulator sickness can nonetheless have a negative impact on VR users.

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Vection that occurs in VR is most often the product of visual input. It has been well known since Gibson (1966) that optic flow patterns on the retina provide a rich source of input for mediating self-motion perception. For example, during daily life an expanding optic flow pattern typically results from forward self-motion whereas a contracting pattern results from backward self-motion. Similarly, in VR the computer-generated optic flow pattern also gives the user information about speed and heading in the virtual environment. This is the case even when other sensory inputs are incompatible with the visual input.

An important assertion underlying the theoretical predictions for the current study is that different optic flow patterns can lead to different types of vection. Just like the self-motion perception that can take place during actual passive travel, vection can be either *steady* or *changing*. These terms are not conventional in the field and thus need to be defined. Steady vection, as the name implies, is defined as vection that is unwavering in terms of its perceived speed and heading. Conversely, changing vection is defined as vection that varies in perceived speed, perceived heading, or both. For example, in a flight simulator, vection may be steady at times, but during maneuvers changing vection is more likely to prevail.

Another point to note is that sensory inputs (visual and nonvisual) that occur during steady vection and actual steady passive travel can be similar (if the head is held steady). In both cases, an optic flow pattern on the retina provides visual input that leads to steady self-motion perception. Nonvisual inputs (e.g., vestibular) that occur during steady vection and actual steady travel can also be similar (Howard, 1982). This is because the vestibular organs only respond to *changes* in heading and/or velocity. Consider traveling in a steadily moving vehicle; closing one's eyes and preventing head movements all but eliminates any percept of self-motion. The vestibular organs may respond to vehicle vibrations, but vestibular and other nonvisual sensory inputs do not provide information about speed and heading when travel is steady.

However, sensory inputs that occur during changing vection and actual travel often differ significantly. During actual travel, the senses often provide inputs that are compatible with each other. In VR this is hardly ever the case. For example, in fixed-base vehicle simulators, the optic flow pattern may lead to changing vection, but vestibular input will typically indicate that no self-motion is occurring. In motion-based simulators, attempts to replicate what the sensory inputs would be under real-life conditions often fall short. Hence, whereas steady vection and steady passive self-motion can result in similar sensory inputs, changing vection and changing passive self-motion often do not. Sensory inputs are more likely to be inconsistent when changing vection is perceived.

It has been reported by Hettinger and colleagues (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990) that individuals who reported vection also indicated higher levels of SS. Their stimulus displays depicted aerial self-motion with changes in roll and pitch as well as displacements in the lateral, longitudinal, and vertical axes. This flight scenario undoubtedly resulted in a high degree of changing vection. Their explanation of the higher incidence of SS when vection is experienced is based on sensory conflict: visually produced self-motion perception in the absence of consistent input from other senses leads to sickness and is considered by some theorists to be a significant causal factor of motion sickness. Sensory conflict has been defined as a lack of sensory input consistency (Reason & Brand, 1975) or as a mismatch between actual sensory inputs and expected sensory inputs obtained from past experience (Oman, 1990).

The hypothesis for the current study is that optic flow indicating changing self-motion will lead to significantly more SS than optic flow indicating steady self-motion. The plausibility of our hypothesis is supported by work conducted using optokinetic drums. Under optokinetic drum conditions, a stationary observer inside a large, rotating cylinder simply views the patterned interior of the drum as it rotates. Circular vection typically occurs within 30 s and motion sickness symptoms often develop after several minutes of viewing (Hu, Stern, Vasey, & Koch, 1989). Optokinetic drum conditions are similar to fixed-base simulator conditions because the

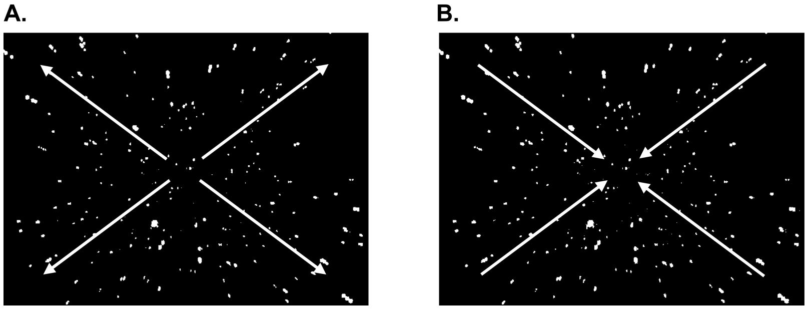

Figure 1. *The stimulus pattern used in Experiment 1 either steadily expanded from the center of the screen (A) or alternately expanded and contracted (A & B).*

observer is stationary relative to earth. The optical flow pattern alone leads to vection.

Work conducted in our lab suggests that compared to a steadily rotating drum, subjective motion sickness scores obtained in a drum that changed rotation direction every 30 s were significantly higher (Bonato, Bubka, & Story, 2005). Similarly, changing drum rotation velocity every 30 s also led to more severe motion sickness symptoms (Bubka, Bonato, Urmey, & Myecewicz, 2006). Finally, if a drum is tilted, so that it rotates in a wobble-like fashion, the vection that is perceived is circular but it also includes a swaying component that in essence is a combination of perceived tilt and roll. Under tilted drum conditions, motion sickness also develops faster compared to a drum that rotates on an earth-vertical axis (Bubka & Bonato, 2003). For the current study, the results obtained using optokinetic drums suggest that changing linear vection resulting from a virtual display may also lead to more SS compared to steady linear vection.

2 Experiment 1

2.1 Method

2.1.1 Overview. In Experiment 1, optic flow patterns displayed on a computer monitor were shown to stationary observers. The experimental setup was designed to emulate the sensory inputs one would expect in a fixed-base simulator. In the *steady condition,* the optical flow pattern viewed expanded from the center of the display monitor at a constant rate. In the *alternating condition,* the optical flow pattern intermittently expanded and contracted. The change in flow pattern was used to 1) reduce the overall vection magnitude given that it usually takes more than 5 s for vection to begin, and 2) increase the probability that any vection perceived would contain a high degree of change (along the fore and aft axis). We hypothesized that sensory conflict would be renewed often in the alternating condition by the flow pattern's frequent changes leading to a subsequent increase in SS.

2.1.2 Participants. Fourteen undergraduate volunteers participated in the experiment (7 males, 7 females, mean age = 19.4 yr). All had normal or corrected-to-normal vision and no one reported any neurological, vestibular, or gastrointestinal problems. All participants reported general good health at the time of the experiment.

2.1.3 Stimuli and Apparatus. The stimulus pattern consisted of an array of light blue squares against a dark background displayed on a 43 cm Dell CRT monitor using an Apple G5 desktop computer (see Figure 1). The monitor resolution was 1,280 × 1,024 pixels and the refresh rate was 85 Hz. The viewing distance was 30 cm, yielding a display that subtended 45° (high) by 53° (wide) of visual angle. The virtual space in the display was 40,000 pixels wide (x) × 40,000 pixels high (y) ×

100,000 pixels deep (z). There were 500 objects in total. Objects were separated in depth by approximately 200 pixels. Objects could be placed in four quadrants (top left, top right, bottom left, bottom right) relative to the $x = 0$, $y = 0$ point at the center of the screen. The density was held constant in each quadrant (125 objects in each). Horizontal and vertical placement within the quadrant was random, with the sole restriction being that the objects could not have an x value less than -640 or greater than $+640$ pixels and a y value less than -512 or greater than $+512$. This represents a square region of 1,280 pixels × 1,024 pixels and prevented elements from "hitting" the observer. No square element was ever closer than 2,000 pixels to the observer. If the z value for an object reached 2,000 pixels, the object was moved 100,000 pixels away, but kept the same horizontal and vertical coordinates it always had.

Perspective was incorporated into the displays; as squares moved from the center of the screen outward (expanding pattern) they increased in size. At maximum size, each element subtended 1.3° of visual angle. As elements expanded, their velocity toward the edge of the screen also increased so as to be consistent with the 3D virtual space. For reference, and in relative terms, the rate of expansion was consistent with an optic flow pattern that would result in an aircraft cruising at a speed of 340 km/h with a visible range of 220 m.

The array of square objects either steadily expanded from the center of the screen (steady condition), or alternately expanded and contracted (alternating condition). In the alternating condition, every 5 s of flow pattern was interrupted by 1 s of a stationary pattern. No interruptions occurred in the steady condition.

Head position was maintained throughout each trial with an optical chin rest that consisted of a depression for the chin and a concave bar to which participants pressed their foreheads. Although participants were instructed to keep their heads stationary throughout trials, the chin rest allowed for slight head shifts in both conditions. An eye patch was used to cover each participant's left eye, resulting in monocular viewing of the stimulus display. The viewing condition has been shown to affect how voluminous a flat display is perceived, and when an optic flow pattern is viewed, the magnitude of vection (Bubka, Bonato, & Mycewicz, 2006). By eliminating stereopsis and vergence, monocular depth cues present in the display (perspective, rates of expansion and contraction) may play more of a role in determining perceived depth, resulting in enhanced three-dimensionality of what is actually a flat display.

2.1.4 Simulator Sickness Assessment Instrument.

SS symptoms were assessed using the Simulator Sickness Questionnaire (SSQ) developed by Robert S. Kennedy and colleagues (Kennedy, Lane, Berbaum, & Lilienthal, 1993). This instrument has frequently been used for measuring symptoms in studies that employed various VR systems. The first page of the questionnaire contains questions about general background, health, alcohol and drug consumption, and simulator experience. The second (pretreatment) and third (post-treatment) pages require participants to rate the severity of known simulator sickness symptoms. When scored according to published guidelines, the SSQ yields four scores: a total SSQ score and three subscores corresponding to nausea, oculomotor (e.g., eye strain, blurred vision) effects, and disorientation. These dimensions of simulator sickness have been identified in a series of factor analyses of large databases.

Sixteen items on the questionnaire contribute to the SSQ scores. Subjects indicate the level of each symptom's severity pretreatment and post-treatment using a Likert-type scale by circling one of four choices (none, slight, moderate, or severe). The 16 symptoms that collectively contribute to the SSQ scores are general discomfort, fatigue, headache, eye strain, difficulty focusing, increased salivation, sweating, nausea, difficulty concentrating, fullness of the head, blurred vision, dizziness with eyes open, dizziness with eyes closed, vertigo, stomach awareness, and burping.

2.1.5 Procedure and Design.

Prior to each trial, the participant completed the first two pages of the SSQ. The participant was then seated in front of the stimulus screen and an eye patch was placed on his or her left eye. The optical chin rest was adjusted so that the participant's right eye was aligned with the center of the monitor screen. At this time the monitor screen was

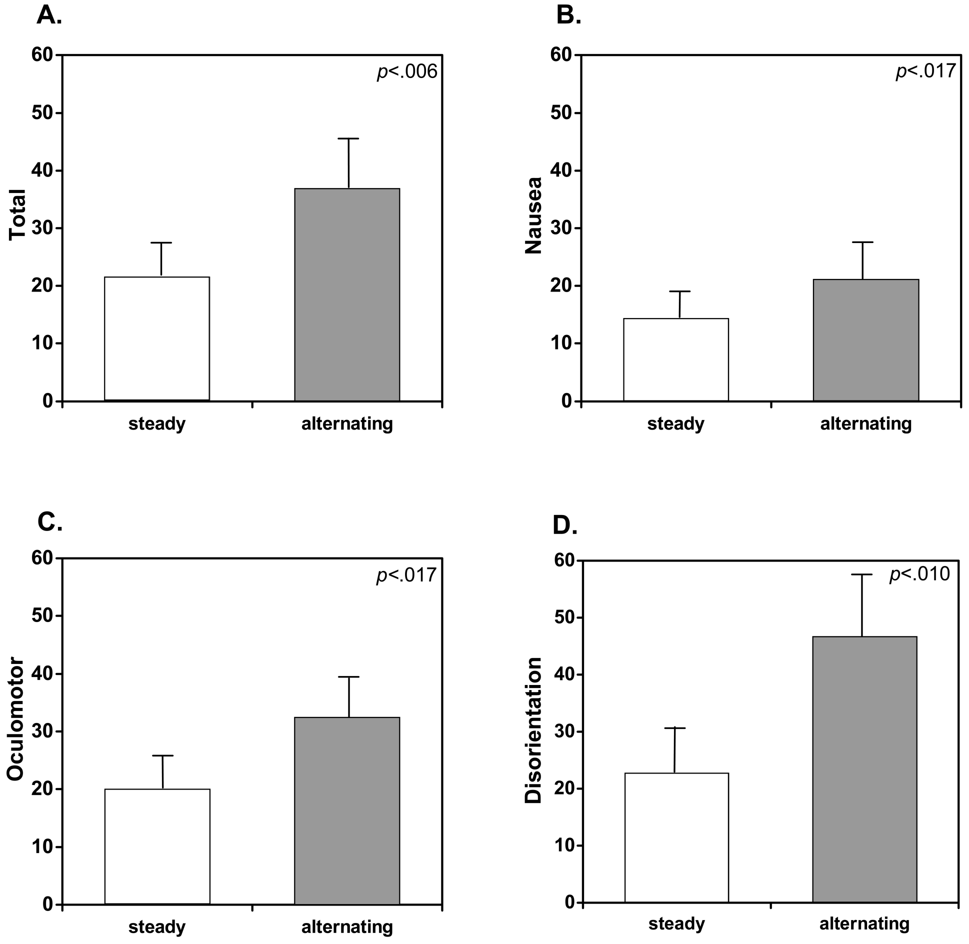

Figure 2. *Results of Experiment 1. Total SSQ scores are shown in (A). Also shown are the mean SSQ subscores for nausea (B), oculomotor symptoms (C), and disorientation (D). Error bars represent the standard error.*

obscured with a baffle and the participant was instructed to close his or her eyes. The lights in the laboratory were turned off, the baffle was removed, and the participant was then instructed to avoid head movements and view the stimulus pattern continuously for 5 min. Immediately after the 5-min viewing period, the laboratory lights were turned on, the participant completed the post-treatment page of the SSQ, and the participant was asked to describe any perception of self-motion that may have occurred. The participant was allowed to rest until any adverse symptoms subsided before leaving the laboratory. Each participant served in both the steady and alternating conditions of the experiment in counterbalanced order. Participation in the two conditions was separated by at least 72 hr.

2.2 Results and Discussion

An analysis of post-treatment scores was conducted. All pretreatment scores indicated no degree of sickness. The results of the post-treatment scores obtained in Experiment 1 are shown in Figure 2. The total SSQ scores (A) obtained in the steady condition (mean = 21.6, $SD = 21.4$) were significantly lower ($t(13) = 2.94$, $p < .006$) than the total SSQ scores obtained in the alternating condition (mean = 36.9, $SD =$

29.6). The nausea SSQ subscores (B) obtained in the steady condition (mean = 14.3, *SD* = 16.2) were also significantly lower ($t(13) = 2.35$, $p < .017$) than those obtained in the alternating condition (mean = 21.1, *SD* = 22.2). Similarly, the oculomotor subscores (C) obtained in the steady condition (mean = 20.0, *SD* = 20.7) were lower ($t(13) = 2.35$, $p < .017$) than the mean subscores obtained in the alternating condition (mean = 32.5, *SD* = 25.3). Finally, the disorientation (D) subscores were lower ($t(13) = 2.64$, $p < .010$) in the steady condition (mean = 22.8, *SD* = 28.7) compared to the subscores obtained in the alternating condition (mean = 46.7, *SD* = 41.1).

These results suggest that an alternating optic flow pattern that intermittently expands and contracts leads to more SS than a steadily expanding pattern. It stands to reason that an alternating pattern is more likely to lead to changing vection, in this case, along the fore and aft axis. Postexperimental reports by observers indicated that this was the case: 1) the steady condition led to forward self-motion that was reported to be predominantly steady, and 2) the alternating condition led to forward-backward self-motion.

In terms of sensory conflict, one might expect the alternating condition to lead to more visual/nonvisual sensory conflict. This is especially true if the expected sensory inputs are compared to those that actually resulted during a trial (Oman, 1990). In the steady condition, visual and nonvisual sensory inputs would be most at odds during the beginning of a trial, but with continued viewing of the steadily expanding pattern, inputs would come to be more similar to those arising during actual passive travel (as long as the participant's head remained stationary). However, in the alternating condition, the frequent direction changes of the flow pattern would serve to make visual and nonvisual inputs be at odds throughout a trial.

3 Experiment 2

Although assumptions were made about vection experience in Experiment 1, it was not measured. In fact, given that vection onset typically takes at least 5 s (Brandt et al., 1973), it seemed important to assess whether or not vection occurred at all in the alternating condition. Hence, the purpose of Experiment 2 was to measure vection with displays that were identical to those used in Experiment 1 (steady and alternating) except for their duration.

Ideally, it would have been informative to measure SS and vection in the same experiment using identical methods. However, Experiments 1 and 2 employed different methods for several reasons. Five minute trials were used in Experiment 1 because this allowed enough time for measurable SS symptoms to develop. However, measurable vection typically occurs faster than SS and thus 5 min trials were not necessary in Experiment 2. Multiple trials were run for each condition (three). Vection measures were taken to be the average of the three trials in an effort to reduce variability that is a common characteristic of vection experiments. Attention demands on participants were also a concern. Significant time was spent instructing participants on using the SSQ in Experiment 1 and the apparatus in Experiment 2. To use the SSQ and the apparatus in the same experiment, although possible, would have made the procedure for each participant more complicated.

We hypothesized that overall vection magnitude would be higher in the steady condition; frequent reversals of the flow pattern in the alternating condition might inhibit vection. Also, every 5 s of flow pattern was followed by 1 s of a static pattern, an arrangement that would further serve to inhibit steady vection. Also, although it was predicted that both conditions would result in some degree of changing vection, the alternating condition due to the frequent changes in flow pattern direction was predicted to result in a higher degree of changing vection.

3.1 Method

3.1.1 Participants. Fourteen undergraduate volunteers participated in the experiment (4 males, 10 females, mean age = 20.6 yr). All had normal or corrected-to-normal vision with no reported history of any neurological, vestibular, or gastrointestinal prob-

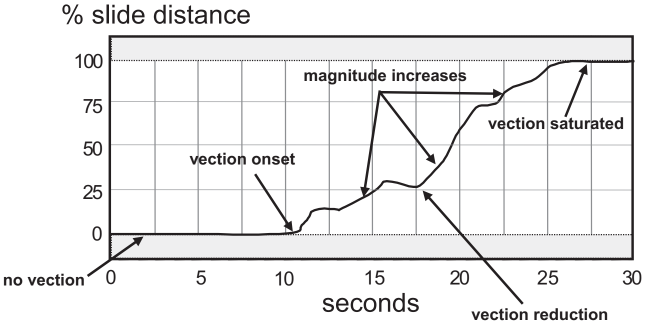

Figure 3. *Sample output for a 30-s trial using the Biopac MP100 data acquisition system. The participant manipulated the slide control on a Biopac TSD-115 variable transducer.*

lems. All reported general good health prior to participating in the experiment.

3.1.2 Stimuli and Apparatus. The stimulus patterns used in Experiment 2 were identical to those used in Experiment 1 except for their duration. Vection was measured using a Biopac MP100 data acquisition system. The participant manipulated the slide control on a Biopac TSD-115 variable transducer using his or her right index finger that was positioned on the same tabletop that supported the display monitor. The slide on the transducer was positioned so that it moved horizontally relative to the participant's line of sight. This arrangement, coupled with explicit instructions, was purposely chosen to help eliminate participants from thinking that the slide should be pushed forward when the flow pattern expanded and vice versa. The system allowed measurement of vection onset (seconds) and magnitude (0–100%) to be recorded with a desktop computer. Sample output for a 30-s trial is shown in Figure 3.

3.1.3 Procedure and Design. A patch was placed on the participant's left eye and his or her head was positioned in an optical chin rest. Instructions were given on how to use the slide control to indicate vection magnitude. Pushing the slide control to the right was meant to indicate that vection was being perceived. Pushing the slide farther to the right was meant to indicate that vection magnitude was increasing. Pushing the slide all the way (5 cm) was meant to indicate that vection was saturated. Careful attention was paid to instructing participants that pushing the slide to the right was meant to be an increase in vection magnitude regardless of whether the flow pattern expanded or contracted. In short, participants were told that the slide had nothing to do with whether or not forward or backward vection was perceived. Three trials were run for each condition; each trial was 30 s long. Each participant's dependent measures were taken to be the mean of the values obtained in the three trials. This averaging was done to reduce variability that tends to be high in these types of experiments. Between trials participants rested for three min before serving in the subsequent trial. Every participant served in both conditions. The order of conditions was counterbalanced. After each condition participants were asked to verbally describe their vection experience.

3.2 Results and Discussion

The results of Experiment 2 are shown in Figure 4. Vection onset and overall vection for each participant were calculated by averaging his or her responses for the three trials. Vection onset latencies in seconds (A) obtained in the steady condition (mean = 8.8, $SD = 6.1$) were not significantly different ($t(13) = 1.35$, $p = .100$) than the latencies obtained in the alternating condition (mean = 10.3, $SD = 7.3$). The overall vection magnitude was defined as the mean amount of slide distance on the variable assessment transducer that resulted for the entire trial. This distance was calibrated on a 0–100 scale (0 = no vection, 100 = vection completely saturated). Overall vection (B) measures obtained in the steady condition (mean = 21.1, $SD = 20.5$) were significantly higher ($t(13) = 2.06$, $p < .030$) than the overall vection measures obtained in the alternating condition (mean = 10.3, $SD = 11.3$). That overall vection magnitude was lower in the alternating condition is not surprising given that: 1) vection direction changed every 6 s, and 2) 20% of the time the display was static. These two factors most likely contributed to vection

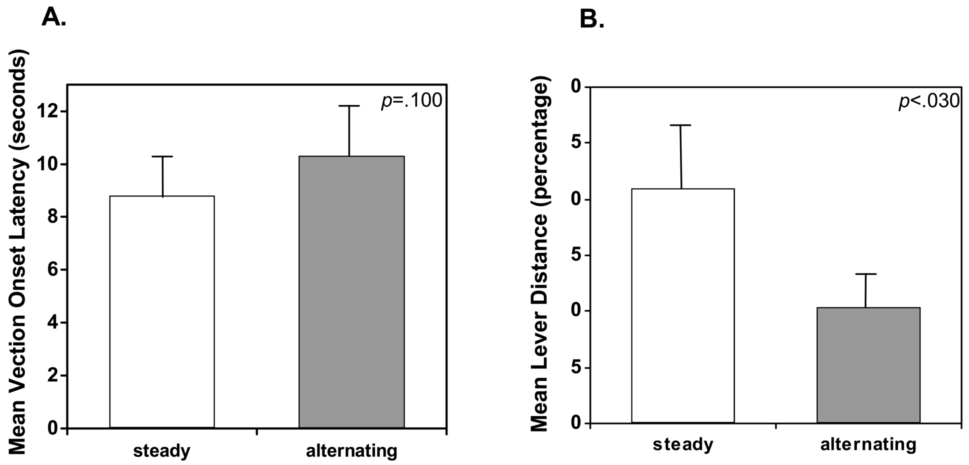

Figure 4. *Results of Experiment 2. Mean vection onset latencies measured in seconds are shown in (A). Mean lever distance percentages (0–100) for the 30-s trials are shown in (B).*

reductions during each trial when vection magnitude either decreased or ceased entirely.

An analysis of vection reductions was conducted. A vection reduction was defined as any reduction of slide distance on the variable assessment transducer of at least 2% of the total possible distance of 100%. This analysis revealed that the mean number of vection reductions obtained (for each 30-s trial) in the steady condition (0.52) was significantly lower ($t(13) = 3.1$, $p < .004$) than the mean number of reductions that occurred in the alternating condition (1.2). In short, these data indicate that more than twice as many reductions occurred in the alternating condition. This finding is in agreement with results that suggest inconsistent sensory inputs can inhibit vection. More specifically, optical flow patterns typically associated with a large degree of expected nonvisual stimulation have been reported to result in weaker vection experiences (Wann & Rushton, 1994). Also, when nonvisual stimulation (e.g., vestibular) occurs during vection that results in a sudden lack of agreement between visual and nonvisual inputs, vection can be diminished or destroyed (Teixeira & Lackner, 1979; Young, Oman, & Dichgans, 1975).

However, it should be noted that other work shows that sometimes increasing the mismatch between visual and vestibular inputs can increase vection magnitude (Palmisano, Gillam, & Blackburn, 2000). In this study, coherent visual field "jitter" was added to radially expanding optical flow patterns. Thus, these jittering displays simulated forward self-motion of a constant velocity combined with continuous, random horizontal and/or vertical impulse self-accelerations (similar to the effects of "camera shake"). It would not be unreasonable to hypothesize that the lack of agreement between visual and vestibular inputs produced by global visual field jitter would inhibit vection. However, Palmisano and his colleagues found that this jitter actually enhanced vection. This work raises the intriguing possibility that because of past experiences of walking and running, visual field jitter is accepted, and perhaps even expected, by the visual system as a normal feature of optical flow patterns.

Although the results of Experiment 2 suggest that less overall vection occurred in the alternating condition, it is important to note that the degree of changing vection perceived in the two conditions differed. In addition to the results of our vection reduction analysis, verbal reports provided by participants unanimously indicated that vection in the alternating condition occurred on the fore-and-aft axis. In short, the alternating condition resulted in forward/backward changing vection. Whereas some changing vection occurred in the steady condition during 1) the beginning of each trial when vection magnitude starts at zero and then generally increases in magnitude; and 2) vection reductions, results suggest that the degree of changing vection that occurred in the steady condition was less than that which occurred in the alternating condition.

4 General Discussion

In most VR systems, the vection that is perceived is often of a changing nature. For example, in the Hettinger et al. (1990) study, participants viewed displays which simulated aerial pitch and roll maneuvers. Although simulated flights can occur during which perceived speed and heading are relatively steady, much like the steady conditions of the current study, there are no published data that indicate how prevalent SS is under those conditions.

In the current study, we examined the SS and illusory experience of self-motion induced by steady and changing vection displays. Although different procedures were used in these two experiments, the displays were identical except for duration. Collectively, the results of these experiments suggest that a steadily expanding optic flow pattern leads to more overall vection but less SS than a pattern that alternately expands and contracts. Thus, if vection magnitude per se leads to symptoms in virtual environments, the steady condition should have led to more SS, but the opposite result was obtained.

Consider what happens in terms of sensory conflict when steady and alternating optical flow patterns are viewed. When the steady pattern is viewed, there is a period of vection onset latency followed by a period during which vection magnitude increases. During this time, because nonvisual sensory inputs (e.g., vestibular) respond to changes in speed and direction (and none of these are occurring), we would expect a high degree of visual/vestibular conflict. In short, the expected set of visual and nonvisual inputs is absent (Oman, 1990). After this period of vection acceleration, vection magnitude typically levels off, yielding a steadier vection percept. Hence, when a steady optic flow pattern is viewed, sensory conflicts should only arise at the beginning of a trial or following a vection dropout. When vection becomes steadier, sensory conflict should be reduced.

However, changing vection should logically lead to a much higher degree of sensory conflict. Because most nonvisual sensory inputs (e.g., vestibular) respond to changes in both direction and speed, changes in the optical flow pattern that are accompanied by unchanging nonvisual input result in a salient conflict. When the stimulus patterns used in the current study alternately expanded and contracted, nonvisual sensory inputs did not change to correspond with the visual input, resulting in visual/nonvisual sensory conflict that may have subsequently led to SS symptoms.

In short, the results of the current study do not refute results obtained by others that suggest vection can lead to SS. However, here we suggest that displays that induce changing vection should lead to more SS. The current results are in agreement with previous results obtained in our lab using optokinetic drums that intermittently changed rotation direction (Bonato et al., 2005), changed rotation velocity (Bubka et al., 2006), and were tilted (Bubka & Bonato, 2003). An increased degree of sensory conflict should typically accompany an experience of changing vection, and this in turn may be a causal factor of SS.

Acknowledgments

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