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Combined Pitch and Roll and Cybersickness in a Virtual Environment

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Abstract

Background: Stationary subjects who perceive visually induced illusions of self-motion, or vection, in virtual reality (VR) often experience cybersickness, the symptoms of which are similar to those experienced during motion sickness. An experiment was conducted to test the effects of single and dual-axis rotation of a virtual environment on cybersickness. It was predicted that VR displays which induced illusory dual-axis (as opposed to single-axis) self-rotations in stationary subjects would generate more sensory conflict and subsequently more cybersickness. Methods: There were 19 individuals (5 men, 14 women, mean age = 19.8 yr) who viewed the interior of a virtual cube that steadily rotated (at 60ÃÂÃÂÃÂÃÂ° ÃÂÃÂÃÂÃÂÃÂ· sÃÂÃÂ¢ÃÂÃÂÃÂÃÂ1) about either the pitch axis or both the pitch and roll axes simultaneously. Subjects completed the Simulator Sickness Questionnaire (SSQ) before a trial and after 5 min of stimulus viewing. Results: Post-treatment total SSQ scores and subscores for nausea, oculomotor, and disorientation were significantly higher in the dual-axis condition. Conclusions: These results support the hypothesis that a vection-inducing VR stimulus that rotates about two axes generates more cybersickness compared to a VR stimulus that rotates about only one. In the single-axis condition, sensory conflict and pseudo-Coriolis effects may have led to symptoms. However, in the dual-axis condition, not only was perceived self-motion more complex (two axes compared to one), the inducing stimulus was consistent with twice as much self-motion. Hence, the increased likelihood/magnitude of sensory conflict and pseudo-Coriolis effects may have subsequently resulted in a higher degree of cybersickness in the dual-axis condition.

Keywords

roll, pitch, combined, virtual, environment, cybersickness

Disciplines

Arts and Humanities | Life Sciences | Medicine and Health Sciences | Social and Behavioral Sciences

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Combined Pitch and Roll and Cybersickness in a Virtual Environment

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Background: Stationary subjects who perceive visually induced illusions of self-motion, or vection, in virtual reality (VR) often experience cybersickness, the symptoms of which are similar to those experienced during motion sickness. An experiment was conducted to test the effects of single and dual-axis rotation of a virtual environment on cybersickness. It was predicted that VR displays which induced illusory dual-axis (as opposed to single-axis) self-rotations in stationary subjects would generate more sensory conflict and subsequently more cybersickness. ***Methods:*** There were 19 individuals (5 men, 14 women, mean age = 19.8 yr) who viewed the interior of a virtual cube that steadily rotated (at $60° \cdot s^{-1}$) about either the pitch axis or both the pitch and roll axes simultaneously. Subjects completed the Simulator Sickness Questionnaire (SSQ) before a trial and after 5 min of stimulus viewing. ***Results:*** Post-treatment total SSQ scores and subscores for nausea, oculomotor, and disorientation were significantly higher in the dual-axis condition. ***Conclusions:*** These results support the hypothesis that a vection-inducing VR stimulus that rotates about two axes generates more cybersickness compared to a VR stimulus that rotates about only one. In the single-axis condition, sensory conflict and pseudo-Coriolis effects may have led to symptoms. However, in the dual-axis condition, not only was perceived self-motion more complex (two axes compared to one), the inducing stimulus was consistent with twice as much self-motion. Hence, the increased likelihood/magnitude of sensory conflict and pseudo-Coriolis effects may have subsequently resulted in a higher degree of cybersickness in the dual-axis condition.

Keywords: pseudo-Coriolis, rotation axis, sensory conflict, vection.

VIRTUAL REALITY (VR) systems often lead to visually induced self-motion perception, or vection, even if the user is stationary relative to Earth. When visual and non-visual inputs are inconsistent regarding self-motion, visual input typically dominates (9), allowing optical flow patterns alone to lead to vection under VR conditions. Often accompanying vection are motion sickness-like symptoms that are often referred to as simulator sickness (14) or, in VR, cybersickness (7). Symptoms can include, but are not limited to, dizziness, headache, salivation, blurred vision, eyestrain, nausea, disorientation, sweating, and pallor. Symptoms can occur in a variety of virtual environments including vehicle simulators (e.g., aircraft, automobile) and while using head-mounted displays (HMDs). Even commercial video games when played using an HMD can lead to symptoms severe enough to make standing subjects terminate participation due to illness (22). In addition to their unpleasantness, the simulator sickness and/or cybersickness experienced during training can delay personnel from engaging in typical duties (e.g., flying).

Multiple causal factors may contribute to cybersickness (17,25) and, like motion sickness, may hence be thought of as polygenic (18). For example, virtual image scaling that deviates from a 1:1 to ratio (11) and postural instability (22) are both associated with more cybersickness for subjects using HMDs. Another possible contributing cause is sensory conflict (23,26). In a VR platform, such as a HMD, visual input alone can indicate that self-motion is occurring. However, sensory inputs that depend on gravity and inertial forces, such as vestibular and proprioceptive inputs, will indicate the user is stationary. It has been suggested that when this type of sensory conflict occurs it may mimic the effects of some neurotoxins and subsequently engage a genetically programmed central nervous system response geared toward ridding the body of poison (vomiting and diarrhea) (27).

Logic suggests that increasing sensory conflict may lead to a stronger central nervous response and subsequently a faster onset of cybersickness and/or more severe symptoms. Studies conducted with physically stationary observers placed inside optokinetic drums that intermittently change direction (4) or rotation speed (6) add plausibility to this hypothesis. Also consistent with this notion, it has been shown that when optic flow induces linear vection in depth in stationary observers, reports of visually induced motion sickness can be increased by either abrupt changes to the simulated direction of self-motion (2) or adding simulated vertical viewpoint oscillation to the display (24).

In the current study two vection-inducing stimuli were presented using a head-mounted VR display. Both stimuli depicted cube-shaped rooms that rotated around the subject. In one display condition, the virtual room rotated about a single axis, the pitch axis. In the other display condition, the virtual room rotated about two axes, the pitch and roll axes. We hypothesized that:

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1) both single and dual-axis rotation of the virtual room would generate significant experiences of vection; and 2) dual-axis rotation would result in a higher degree of sensory conflict and hence more cybersickness.

METHODS

Subjects

There were 19 Saint Peter's College undergraduate students who voluntarily participated in the experiment (5 men, 12 women). The age of subjects ranged from 18 to 22 yr (mean = 19.8 yr). Persons reporting any visual, vestibular, neurological, gastrointestinal abnormality, or any other health problem, were not allowed to participate. Subjects fasted for at least 2 h before each trial. The Saint Peter's College Institutional Review Board approved the study in advance. Each subject provided written informed consent before participating in the study.

Stimuli and Apparatus

Subjects viewed the interior of a virtual room using an nVisor SX HMD. The HMD had a monocular field-of-view of 60° diagonal and a resolution of 1280 × 1024 pixels at 60 Hz. Stimuli were presented in stereo mode with an interpupillary distance setting of 6 cm. The stimulus was programmed in Python and rendered using Vizard software; it consisted of a virtual cubic room that contained a black and white checkerboard pattern on each wall (256 squares). Stereo rendering was consistent with a 5-m cubic room. In order to enhance depth perception in the virtual space, subjects viewed the cube's interior from their simulated vantage point in the middle of the room through a vertical scaffold (see **Fig. 1**). The virtual room rotated either solely about the subject's pitch axis (upward) or simultaneously about his/her roll (clockwise) and pitch axes. Rotation speed about each axis was steady at 10 rpm ($60° \cdot s^{-1}$).

Cybersickness Assessment Instrument

Motion sickness symptoms were assessed using the Simulator Sickness Questionnaire (SSQ) (20). The SSQ has frequently been used for measuring symptoms in studies that employ virtual environments. When scored according to published guidelines (16), the SSQ yields four scores: a total SSQ score and three subscores corresponding to nausea, oculomotor effects, and disorientation. There were 16 items on the questionnaire (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) used to calculate SSQ scores. Subjects indicated the level at which each symptom was experienced both pre-treatment and post-treatment by circling one of four choices (none, slight, moderate, or severe).

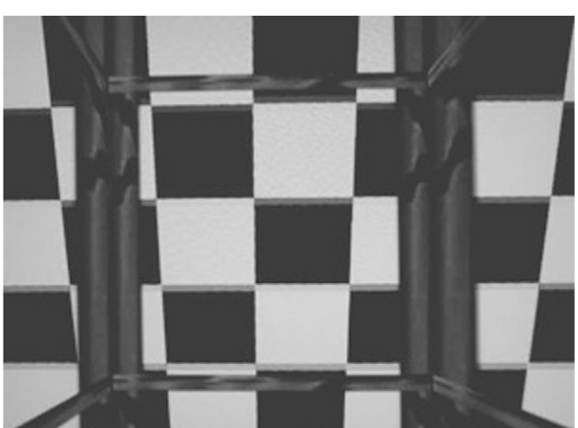

Fig. 1. Interior view of virtual cube-shaped room as seen through the HMD.

Procedure and Design

The subject was given instructions regarding the SSQ before proceeding to fill out the pre-treatment page of the SSQ form. The subject was then seated and the HMD was placed on his/her head and adjusted. The subject was instructed to close his/her eyes until the stimulus appeared and to keep his/her head still while watching the rotating room. After 5 min of viewing, the subject was instructed to close his/her eyes, the HMD was removed, and the subject was immediately given the post-treatment portion of the SSQ form to complete.

Each subject served in both the single-axis and dual-axis rotation conditions. Participation was completely counterbalanced to control for any possible order effects, including adaptation. At the conclusion of each trial, the subject rested until the severity of symptoms subsided. The subject was scheduled for a subsequent condition in 48-72 h. At the conclusion of the second trial, subjects were asked to compare the two conditions and to indicate which one, if any, made them feel sicker.

RESULTS

Four scores were calculated for each subject using published methods and weighting factors (20): a total SSQ score and three subscores for nausea, oculomotor symptoms, and disorientation. The means obtained for all four scores are shown in **Fig. 2**. The mean total SSQ scores in the single-axis and dual-axis conditions were 15.4 and 25.4, respectively. A *t*-test for repeated measures (one-tailed) revealed that the mean total SSQ score was significantly lower in the single axis condition [$t(18) = 2.9$, $P < 0.005$]. The mean SSQ subscore for nausea (9.5) obtained in the single-axis condition was significantly lower [$t(18) = 1.9$, $P < 0.035$] than the mean nausea subscore obtained in dual-axis condition (15.6). The mean SSQ subscore for oculomotor symptoms (10.8) obtained in the single-axis condition was significantly lower [$t(18) = 3.7$, $P < 0.001$] than the mean oculomotor subscore obtained in the dual-axis condition (20.0). The mean SSQ subscore for disorientation (23.4) obtained in the single-axis condition was significantly lower [$t(18) = 1.9$, $P < 0.04$] than the mean disorientation subscore obtained in the dual-axis condition (35.2). When given a forced choice at the conclusion of the experiment, subjects unanimously

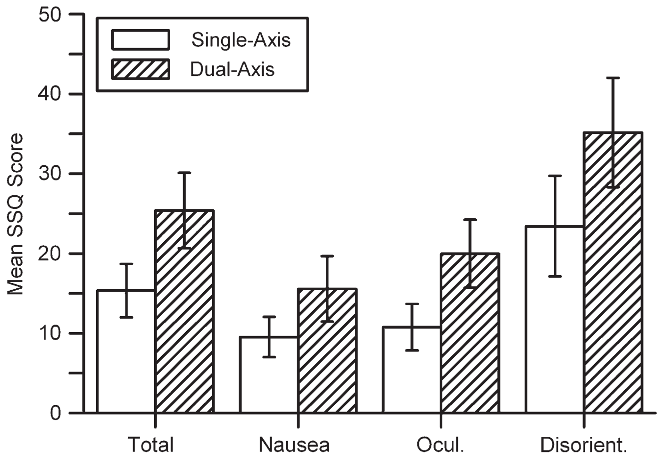

Fig. 2. Mean post-treatment SSQ total scores and subscores for nausea, oculomotor symptoms, and disorientation. Error bars represent ± one standard error of the mean.

indicated that the dual-axis condition made them feel sicker than the single-axis condition.

The SSQ also includes a question regarding self-motion perception. Subjects were prompted to indicate using a 0-10 scale the degree of self-motion that was perceived during a trial. The mean self-motion rating obtained in the single-axis condition was 5.8 and in the dual-axis condition it was 6.5. Although these mean ratings suggest that moderate to strong vection was induced by both conditions, they were not significantly different from each other [$t(18) = 1.3$, $P = 0.11$]. We note that the type of vection perceived by subjects was often complex. Verbal reports suggested that simultaneous sensations of self-motion and self-tilt were often perceived; however, full "head-over-heels" vection was rare, presumably due to the inconsistency of the visual input with that provided by the gravireceptors (the otolith and somatosensory systems) and the lack of visual polarity cues in the VR display (15). We suggest an explanation of these results based on the differing degrees of sensory conflict generated by our two experimental conditions.

DISCUSSION

The results of the current study suggest that a vection-inducing VR stimulus that rotates about two axes generates significantly more cybersickness compared to a VR stimulus that rotates about only one. The mean total SSQ score obtained in the dual-axis condition was 65% higher than the mean score obtained in the single-axis condition. Also, nausea, oculomotor, and disorientation subscores were, respectively, 64%, 85%, and 59% higher in the dual-axis condition. Although it would be incorrect to assume that higher SSQ scores always indicate that subjects feel "sicker," higher scores are consistent with what one would expect from someone who is experiencing cybersickness symptoms. The total SSQ score obtained in the dual-axis condition of the current experiment would normally be considered high enough to indicate a "problem simulator" (17). Measuring cybersickness (like motion sickness) is difficult; there is no hard and fast standard to abide by except perhaps vomiting, which many institutional review boards (including our own) consider unethical. We acknowledge that many, if not all, of the symptoms that subjects rate using the SSQ can occur for a variety of different reasons. Although a measure such as vomiting would enhance our confidence that subjects were truly sick, the mean SSQ scores that were obtained in the dual-axis condition are consistent with a VR set-up that is problematic in terms of its resulting symptoms. Also, higher nausea subscores obtained in the dual-axis conditions seem to be particularly suggestive of sickness.

The results of the current study are consistent with findings reported for actual self-motion (13) that addressed the well-known 0.2 Hz dominant frequency that is particularly nauseogenic for vertical (heave) oscillation. Even though the waveforms used in the current study were more complex (compared to heave alone) and the self-motion perceived was illusory, the frequency we used (0.17 Hz) was similar. We acknowledge that although the stimuli we used were consistent with pitch and roll self-motion, a heave component is introduced for the vestibular organs that would oscillate up and down had the pitch and roll motion been actual relative to Earth.

One could reasonably hypothesize that the differences obtained in the current study were simply due to the roll component in the dual-axis condition. In short, if roll vection is more provocative for motion sickness/cybersickness than pitch vection, there would be no reason to surmise that the addition of pitch and roll was responsible for the exacerbation of these symptoms. However, previously reported results ($P = 0.69$) obtained using the same apparatus and stimulus conditions suggest that there is no significant difference for SSQ scores when pitch and roll were tested independently (3). Furthermore, recent results reported by Joseph and Griffin revealed no differences for motion sickness in individuals subjected to either pitch or roll oscillation of the same magnitude and frequency (16). Hence, it seems unlikely that the current results simply reveal a more provocative effect of roll vection compared to pitch vection.

Stimuli in the current study were consistent with illusory self-rotation about two orthogonal axes. However, the vection reported by subjects was not "head-over-heels" in nature. Instead, self-motion perception was reported that was sometimes intermittent (variable) and accompanied simultaneously by a sensation of tilt. These reports suggest that more changing vection, as opposed to steady vection, was perceived. It has been previously reported that compared to steady vection, changing vection exacerbates motion sickness symptoms (2,4,6). An increased degree of changing vection in the dual-axis condition would hence be predicted to lead to more sickness. Here, however, we are careful to note that twice as much stimulus motion occurred in the dual-axis condition. Hence, it is not possible to disambiguate the effects of "more axes of motion" from simply "more motion." While the mean self-motion ratings for our single- and dual-axis conditions were not significantly different, the possibility that more stimulus movement resulted in the exacerbation of symptoms in the latter conditions cannot be fully discounted.

Coriolis forces are generated during physical observer rotation along two orthogonal axes (e.g., when tilting one's head toward the shoulder during a yaw self-rotation). These Coriolis forces are known to induce apparent tilt, dizziness, nausea, and extreme discomfort (12). Importantly, pseudo-Coriolis effects (8), very similar to these Coriolis effects, can also be induced during circular vection when observers make real head-movements along one or another orthogonal axis. During our experiment, even slight movements of the observer's unrestrained head could have caused pseudo-Coriolis effects and it would be reasonable to assume that they did occur in both the single-axis and dual-axis conditions of the current experiment. In the dual-axis condition, illusory self-rotation occurred around two orthogonal axes, a condition that may have led to pseudo-Coriolis effects even in the absence of any "true" body rotation. Combined with any slight head movements and the variable nature of the vection that resulted, these pseudo-Coriolis effects may have been responsible for the greater cybersickness experienced in the dual-axis condition.

The results of the current experiment are consistent with those obtained for subjects exposed to $60° \cdot s^{-1}$ optokinetic drum stimulation with the drum either aligned to the earth-vertical axis (yaw), or tilted relative to the axis of rotation (5° and 10° tilt) (5). The "wobbling" drum led to a complex sort of vection that in addition to yaw included oscillating pitch and roll components. Results suggested that subjective motion sickness symptoms were significantly worse in the tilted drum conditions. The current results are somewhat consistent with those obtained for subjects who viewed the interior of an optokinetic drum that contained either vertical or off-vertical (15°) stripes (1). The off-vertical condition yielded vection that included both a rotational component (yaw) and a vertical linear component. Significantly more gastric tachyarrhythmic activity also resulted in the off-vertical condition (consistent with an increased degree of motion sickness), although no significant differences were found for subjective motion sickness measures. When compared to results obtained using actual self-motion, there is also some consistency between our results and those obtained for seasickness. Although it has been assumed by many that seasickness is uniquely provoked by heave motion, adding pitch and roll components exacerbates symptoms (28). Also, pitch and roll motions when combined led to somewhat higher sickness scores compared to a roll-only experiment (28).

To be fair, we note that the current results do not agree with those reported for subjects who viewed patterns that were consistent with single-axis self-motion (roll or linear) or dual-axis self-motion (10). The dual-axis condition combined roll and linear components and was consistent with spiral self-motion. The authors' hypothesis was essentially the same as ours: increased sensory conflict during exposure to dual-axis vection-inducing stimuli would exacerbate symptoms compared with exposure to the roll or linear components in isolation. However, no statistically significant differences between dual-axis and single-axis conditions were revealed (10). It is difficult to account for the differences between the two studies without conducting further research. However, we note that their combined linear and rotary optic flow (10) was qualitatively different to the combination of two rotary flows examined in the current study.

Although the effects of dual-axis rotation (and more complex pseudo-Coriolis effects) cannot be fully teased apart from the possible effects of more (twice) stimulus motion, both explanations are consistent with the sensory conflict theory of motion sickness (26). Sensory conflict and motion sickness symptoms would both be expected to increase if significantly faster self-motion was perceived from the visual input used in the dual-axis conditions compared to the single-axis conditions (since non-visual sensory information about self-motion and self-orientation were similar in both the single- and dual-axis conditions). As noted above, while our subjects mean self-motion ratings indicated a trend in this direction, they were not significantly different. This suggests that when it was present, the dual-axis nature of the visually simulated self-rotation also exacerbated the subject's experience of sensory conflict and cybersickness. Any slight head movements made during single- or dual-axis simulated self-rotation would have resulted in pseudo-Coriolis effects. However, in the dual-axis condition, where the displays simulated self-motion about both the roll and pitch axes (instead of just roll), the likelihood of such sensory conflicts/pseudo-Coriolis effects would have been much higher, leading to an exacerbation of cybersickness symptoms.

In summary, we have found that in VR, simulated rotary self-motion about two axes leads to increased sensory conflict and subsequently more cybersickness compared to simulated rotary self-motion about one axis. These results may be due to an increase in the likelihood and/or magnitude of changing vection and pseudo-Coriolis effects in the dual-axis condition or simply more stimulus motion. Both explanations are consistent with the sensory conflict theory of motion sickness (26). We acknowledge that cybersickness can be caused by other factors (e.g., lag, accommodation/vergence mismatch) (21). However, given that the only difference in the two conditions of the current experiment was the type of self-rotation simulated, it seems unlikely that other factors could account for the differences revealed. Several subjects spontaneously reported that after the experiment was over, some unpleasant symptoms lingered and in some resurfaced after several hours. These possible long-term effects of VR are problematic in that cybersickness may negatively affect activities that occur hours after VR exposure. Recent research (19) suggests that although they subside, cybersickness symptoms can persist at least up to 1 h after exposure.

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