Rotation Velocity Change and Motion Sickness in an Optokinetic Drum

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Background: Stationary subjects who view the interior of an optokinetic drum often experience motion sickness (MS) symptoms, perhaps because visual and vestibular sensory inputs are in conflict. It was predicted that intermittently changing drum rotation velocity would cause an increase in sensory conflict, and subsequently lead to more MS. Visual input indicating frequent changes in self-motion would not be consistent with vestibular input indicating no self-motion. When drum rotation is steady, visual and vestibular inputs are more likely to agree given that the vestibular organs only respond to change. ***Methods:*** There were 12 individuals who participated in the experiment (7 men, 5 women, mean age = 24.0 yr). In two conditions subjects viewed the interior of an optokinetic drum that steadily rotated at either 5 RPM or 10 RPM. In a third condition drum velocity alternated every 30 s between 5 RPM and 10 RPM (5/10 RPM condition). In all conditions the subject's head was immobilized in the center of the drum that rotated on an Earth-vertical axis. Subjects completed the Simulator Sickness Questionnaire (SSQ) designed by Kennedy and colleagues both before a trial and after 4 min of drum viewing. A total SSQ score and three SSQ sub-scores (nausea, oculomotor, and disorientation) were obtained. ***Results:*** Mean post-treatment total SSQ scores (mean = 41) were significantly the highest in the 5/10 RPM condition followed by the conditions of steady rotation velocity at 10 RPM (mean = 36) and 5 RPM (mean = 24). Likewise, mean nausea sub-scores were also the highest (mean = 24) in the 5/10 RPM condition followed by the 10 RPM condition (mean = 19) and the 5 RPM condition (mean = 11). ***Conclusions:*** These results support the hypothesis that a conflict between sensed and expected effects of self-motion alone can lead to MS. Changing rotation velocity increases sensory conflict that in turn leads to more MS.

Keywords: rotation velocity, motion sickness, optokinetic drum, sensory conflict, vection.

IT HAS BEEN WELL documented that motion sickness (MS) often occurs in optokinetic drums. Under optokinetic drum conditions a stationary subject inside a large rotating cylinder simply views the drum's interior that typically consists of a high contrast pattern of stripes or dots. Within 30 s vision usually leads to a perception of passive self-rotation (vection) while the vestibular system continues to indicate that no self-rotation is occurring. After several minutes MS symptoms may occur, a result that has often been explained in terms of a visual/vestibular sensory conflict (6,8,9).

The current study was designed to test if increasing visual/vestibular conflict would lead to more MS. More specifically, we tested the hypothesis that conflict regarding sensed and expected self-motion alone would affect MS. Given that the vestibular system responds to changes in tilt and velocity, an attempt was made to isolate the effects of changing velocity by holding the effects of tilt constant across conditions. This was accomplished by positioning each subject's head on the axis of rotation of an optokinetic drum that rotated on an Earth-vertical axis.

In two conditions of the current study, the drum rotated at a constant velocity. It was predicted that these conditions would initially lead to visual/vestibular sensory conflict, but because the vestibular system only responds to change, the degree of conflict would lessen with time. At the beginning of a trial, the self-motion that is sensed visually, leading to vection, is not sensed by the vestibular system. The expected vestibular input that would be consistent with accelerating vection is absent. However, as vection becomes a steadier perceptual state, sensed and expected vestibular inputs become more alike because the vestibular system only responds to velocity changes in this case. In other words, the sensory inputs that occur during vection and actual self-rotation become more alike with the passage of time.

However, in one condition of the current study drum rotation velocity was changed every 30 s. It was predicted that in this condition the frequent changes in rotation velocity would lead to more sensory conflict and subsequently more MS. When the head is immobilized vestibular input (sensed) will correctly indicate that the person is stationary. However, expected vestibular input will change every time drum rotation velocity changes. The result: a sensory conflict regarding the sensed and expected effects of self-motion. In this case, the expected effects of self-motion on vestibular input would be the result of drum rotation velocity changes and the subsequent changes in vection velocity.

The plausibility of our hypothesis is derived from the results of a recent experiment during which changing drum rotation direction every 30 s led to more MS

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compared with an optokinetic drum that rotated in the same direction (3). The theoretical motivation for the hypothesis in that previous experiment is the same here: can increasing the degree of conflict between sensed and expected effects of self-motion alone hasten MS onset in an optokinetic drum? Whereas in our previous experiment the manipulation was qualitative in nature (direction change), in the current experiment the manipulation was quantitative (velocity change). A rival hypothesis regarding our previous rotation direction change experiment is that the obtained results were the result of direction-specific adaptation. In the current experiment rotation direction did not change, thus rendering a hypothesis based on direction-specific adaptation inapplicable.

METHODS

Subjects

There were 12 Saint Peter's College undergraduate students and faculty members who voluntarily participated in the experiment (7 men, 5 women). The age of subjects ranged from 19 to 46 yr (mean = 24.0 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 (IRB) approved the study in advance. Each subject provided written informed consent before participating in the study.

Apparatus

The optokinetic drum consisted of a synthetic composite cylinder 122 cm in height and 107 cm in diameter. The cylinder was mounted in a sturdy frame, yielding a drum that was completely rigid. The drum was suspended from a motor attached to a beam directly above the drum with four steel cables. Given the mass of the drum, and the position of the cables supporting it, this method of suspending the drum resulted in a smooth and steady rotation, free of any wobble or sway after 2 s of rotation (at 5 RPM or $30° \cdot s^{-1}$). Head position was maintained throughout the experiment by means of an optical chin rest in which the subject's chin rested in a stationary concave depression while the subject's forehead rested against a curved metal bar. Viewing took place with the subject's head centered at the axis of rotation. This resulted in a viewing distance of 48.5 cm when the subject's line of sight was perpendicular to the drum's surface. Horizontally positioned baffles attached to the top and bottom of the chin rest restricted the subject's view so that the only surface seen through the baffles was the interior of the drum. Illumination was provided by two 32-W florescent bulbs positioned directly behind a translucent plastic diffuser panel and 102 cm above the top of the drum. The stimulus pattern that lined the interior of the drum consisted of 12 alternating black and white vertical stripes. The width of each stripe subtended 30° of visual angle. The black and white stripes had luminance values of 1.6 and 36.0 $cd \cdot m^{-2}$, respectively.

Assessment Instrument

MS symptoms were assessed using the Simulator Sickness Questionnaire (SSQ) developed by Robert S. Kennedy and colleagues (7). This instrument has frequently been used for measuring MS symptoms in studies that employed both simulators and optokinetic drums. The first page of the questionnaire contains questions about general background, health, alcohol and drug consumption, and simulator experience. The second (pre-treatment) and third (post-treatment) pages require participants to rate the severity of known simulator sickness symptoms. When scored according to published guidelines (7) the SSQ yields four scores: a total SSQ score and three sub-scores corresponding to nausea, oculomotor effects (e.g., eye strain, difficulty focusing), and disorientation. The three sub-scores have been identified in a series of factor analyses of large databases as being measures of the main components of motion sickness. There are 16 items on the questionnaire that contribute to the SSQ scores. Subjects indicate the level at which each symptom is experienced both pre-treatment and post-treatment 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.

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 inside the optokinetic drum and instructed to close his/her eyes until the drum steadily rotated either at a speed of 5 RPM or 10 RPM, depending on the condition. After being instructed to open his/her eyes and viewing the drum for 30 s, the subject was then instructed to close his/her eyes for 5 s. On opening his/her eyes, drum rotation was either the same (5 RPM and 10 RPM conditions) or it had changed (5/10 RPM condition). In the 5/10 RPM condition, drum velocity alternated between 5 RPM and 10 RPM every 30 s. In this condition, half of the subjects first viewed the drum rotating at 5 RPM and the other half first viewed the drum rotating at 10 RPM. In the 5 RPM and 10 RPM conditions, drum velocity remained constant throughout the trial. After 4 min of drum viewing, the subject was instructed to close his/her eyes, drum rotation was stopped, and the subject was then led out of the optokinetic drum. The subject was immediately given the post-treatment portion of the SSQ form to complete.

Each subject served in all three conditions: 1) 5 RPM (steady velocity); 2) 10 RPM (steady velocity); and 3) the 5/10 RPM (alternating velocity). There were six possible orders of participation. 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 subse-

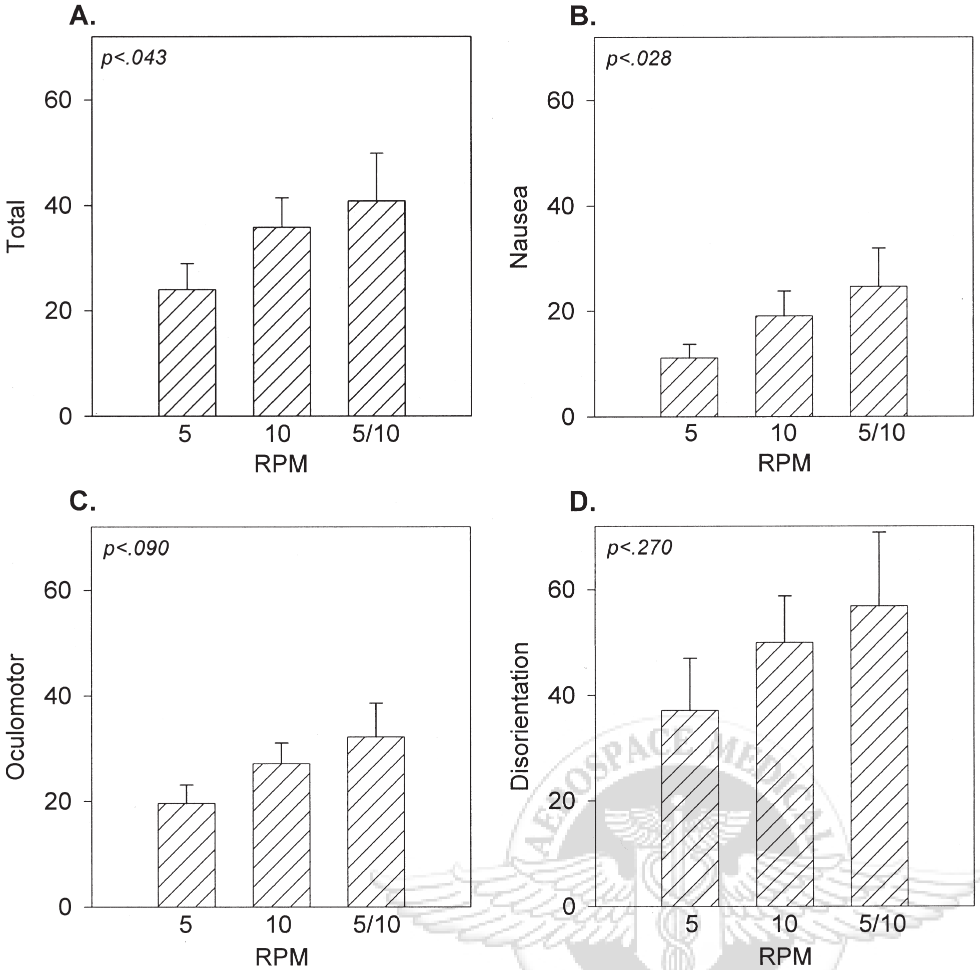

Fig. 1. Mean Simulator Sickness Questionnaire (SSQ) scores obtained in the experiment after 4 min of optokinetic drum exposure: A) total SSQ scores; and mean sub-scores for B) nausea, C) oculomotor effects, and D) disorientation. Error bars represent the standard error of estimate.

quent condition in 48–72 h. The time period between conditions served to allow any residual motion sickness symptoms from previous conditions to subside before the subject participated in a subsequent condition.

RESULTS

Four scores were calculated for each subject using methods and weighting factors outlined in Kennedy et al. (7): a total SSQ score and three sub-scores for nausea, oculomotor symptoms, and disorientation. The means obtained for all four scores are shown in **Fig. 1**. The mean total SSQ scores in the 5 RPM, 10 RPM, and the 5/10 RPM conditions were 24, 36, and 41, respectively (see Fig. 1A). A one-way repeated measures ANOVA revealed a significant effect among conditions [$F(2,22) = 3.6$, $p < 0.043$]. A Tukey HSD post hoc analysis indicated that the mean total SSQ score in the 5 RPM condition was significantly lower than the mean total SSQ score obtained in the 5/10 RPM condition ($p < 0.05$). The means obtained in the 10 RPM condition were not significantly different from the means obtained in the 5 RPM and 5/10 RPM conditions.

The mean SSQ sub-scores obtained for nausea were 11, 19, and 24, respectively, for the 5 RPM, 10 RPM, and 5/10 RPM conditions (see Fig. 1B). A one-way repeated measures ANOVA revealed a significant effect among conditions for nausea [$F(2,22) = 4.2$, $p < 0.028$]. A Tukey HSD post hoc analysis indicated that the mean nausea sub-score in the 5 RPM condition was significantly lower than the mean total SSQ score obtained in the 5/10 RPM condition ($p < 0.05$). The means obtained in the 10 RPM condition were not significantly different from the means obtained in the 5 RPM and 5/10 RPM conditions.

The mean SSQ sub-scores obtained for oculomotor symptoms were 20, 27, and 32, respectively, for the 5 RPM, 10 RPM, and 5/10 RPM conditions (see Fig. 1C). A one-way repeated measures ANOVA did not reveal any significant effect among conditions for oculomotor symptoms [$F(2,22) = 2.7$, $p = 0.09$], although the differences obtained approached significance. The mean SSQ sub-scores obtained for disorientation were 37, 50, and 57, respectively, for the 5 RPM, 10 RPM, and 5/10 RPM conditions (see Fig. 1D). A one-way repeated measures ANOVA did not reveal any significant effect among conditions for disorientation [$F(2,22) = 1.4$, $p = 0.27$].

DISCUSSION

The results of the current study indicate that intermittently changing optokinetic drum rotation velocity results in significantly more MS compared with a steadily rotating drum. The mean total SSQ score obtained in the 5/10 RPM condition was 50% higher than the mean score obtained in the 10 RPM condition and 71% higher than the mean score obtained in the 5 RPM condition. Likewise, the mean nausea sub-score obtained in the 5/10 RPM condition was 73% higher than the mean nausea sub-score obtained in the 10 RPM condition and 119% higher than the mean nausea sub-score obtained in the 5 RPM condition.

An analysis of how changing drum rotation velocity results in a self-motion mismatch follows. Consider what sensed and expected self-motion would be in a steadily rotating drum. When the drum begins to rotate, vestibular and visual inputs will not be in agreement; vestibular input will continue to indicate that the subject is stationary while visual input will indicate self-acceleration. As the drum continues to rotate steadily, vection will typically occur and become a steadier perceptual state; vestibular and visual inputs come to be less at odds. Furthermore, if vection becomes fully saturated, vestibular stimulation should be the same as if actual passive self-rotation were occurring. In short, as vection becomes steadier the degree of conflict regarding vestibular and visual conflict is reduced. It is at the beginning of a trial, when vection is accelerating (and during vection dropouts if they occur), that the greatest disparity occurs in a steadily rotating optokinetic drum. This analysis is based on the assumption that the vestibular system responds to changes in heading and/or velocity.

In the 5 RPM and 10 RPM conditions of the current study, when drum rotation was steady, there were 5-s intervals occurring every 30 s when the subject had his/her eyes closed. However, on opening his/her eyes, drum rotation was the same as it was previously. In a previous experiment the authors obtained results that suggest under these types of conditions, vection onset is significantly faster after the initial viewing has taken place (2). In other words, vection tends to pick up where it left off; the time it takes to "ramp up" to steady vection is significantly shortened. It is as if an expectation exists regarding optical flow patterns that allows for a brief interruption in the input (in this case visual). Logically, a mechanism that allows for such interruptions must exist and would account for the seamless self-motion perception we typically experience despite frequent interruptions of visual input such as those that occur during blinking and gaze shifts to other scenes. In addition to providing a stable self-motion percept, such a mechanism would also serve to reduce sensory conflict, and for the purpose of the current argument, a sensory conflict regarding sensed and expected self-motion in particular.

The 5/10 RPM condition resulted in an arrangement during which sensed and expected effects of self-motion were more at odds throughout an entire trial. Consider what happens after viewing a drum rotating at 5 RPM for 30 s and then subsequently the same drum rotating twice as fast (10 RPM). At 5 RPM the vestibular and visual inputs came to be increasingly more in agreement as vection magnitude became steadier; when the 10 RPM flow pattern was viewed instead, the lack of agreement between vestibular and visual inputs suddenly increased as vection accelerated in response to the faster moving optical flow pattern. Vestibular input continued to relay the same information in all trials: no self-motion was occurring. It was the visual input that changed significantly every 30 s in the 5/10 RPM condition. Like our previous experiment during which rotation direction was intermittently changed (3), intermittently changing drum velocity yields a condition during which there is an almost constant state of disagreement regarding visual and vestibular inputs. There is conflict in the 5 RPM and 10 RPM conditions as well, and this would account for the MS symptoms that resulted in those conditions, but the degree of conflict in those conditions would be less compared with the 5/10 RPM changing velocity condition.

The results of the current study do not support the sensory conflict theory proposed by Bles and colleagues (1). Their theory asserts that only situations that lead to a mismatch in sensed vertical and expected gravitational vertical yield MS symptoms (1). The sensed vertical is determined through integrated inputs from the eyes, vestibular system, and proprioceptive system. The expected vertical is predicted on the basis of past experience. According to this subjective vertical mismatch theory (1), MS should not occur in an optokinetic drum when: 1) the drum rotates on an Earth-vertical axis; 2) the subject's head is immobilized and centered at the rotation axis; and 3) vertical stripes are used. Under these conditions sensed and expected verticals should be in agreement.

When sensed and expected vertical do not agree, such as when observers are placed in a tilted optokinetic drum that rotates in a wobble-like fashion (5), it has been reported that more MS results. Such a finding can be explained in terms of a subjective vertical mismatch (1,4). However, our theory based on a mismatch between the sensed and expected effects of self-motion can equally explain the results of our tilted drum experiment (5). In addition to perceiving circular vection, subjects in a tilted drum perceive self-motion in the form of swaying or wobbling. The swaying percept is visually induced but it is not accompanied by what would be the expected vestibular stimulation; sensed vestibular input indicates that no self-motion is occurring. In short, vertical mismatch (1,4) and a sensed and expected mismatch pertaining to self-motion can both explain increased MS in a tilted optokinetic drum. The tilted drum experiment (5) did not constitute a test of the two theories.

The results of the current study suggest that a mismatch regarding sensed and expected gravitational vertical is not a necessary condition for evoking MS. Given that the optokinetic drum used in this study was rigid, rotated steadily on an Earth-vertical axis, and subjects' heads were carefully aligned with the axis of rotation, it seems unlikely that a subjective vertical mismatch could have occurred under these experimental conditions. Instead, like previous results that showed changes in rotation direction lead to more MS (3), these results also suggest that a mismatch between sensed and expected passive self-motion alone can lead to MS.

It could be argued that slight head movements occurred even though an optical chin rest was used to position subjects' heads and these head movements could have resulted in a vertical mismatch and thus account for the MS that was measured. The authors do not deny this possibility. However, given that the drum rotated on the same Earth-vertical axis in all three conditions and the amount of time subjects spent in each condition was exactly the same, it seems unlikely that head movements could have caused the differences obtained among conditions.

Subjective vertical mismatch may affect MS, but as the previously reported rotation direction change (3) and the rotation velocity change experiment reported here suggest, vertical mismatch does not seem to be the sole causal factor responsible for MS. The challenge now exists to design and conduct an experiment during which sensed and expected vertical are manipulated in the absence of a sensed and expected self-motion mismatch.

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