Rotation Direction Change Hastens Motion Sickness Onset in an Optokinetic Drum

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Background: Many stationary subjects who view the patterned interior of a rotating cylinder (optokinetic drum) experience motion sickness (MS) symptoms. An experiment was conducted to investigate the effects of rotation direction change on MS onset and severity. It was predicted that intermittently changing rotation direction would hasten MS onset due to an increased degree of visual/vestibular sensory conflict. ***Methods:*** There were 12 individuals who participated in the experiment (4 men, 8 women, mean age = 24.4 yr). Subjects viewed the interior of an optokinetic drum that rotated at 5 rpm ($30° \cdot s^{-1}$). Drum rotation was either consistently in the same direction or rotation direction changed every 30 s. Eight MS symptoms were assessed at 2-min intervals using a subjective scale (0 = none, 1 = slight, 2 = moderate, 3 = severe). ***Results:*** Overall, MS onset was fastest when drum rotation direction changed. Specific MS symptoms significantly affected were dizziness, stomach awareness, and nausea. ***Conclusions:*** These results suggest that a lack of correlation between the sensed and expected effects of motion alone can lead to MS. These results cannot be accounted for by a lack of correlation between sensed and expected gravitational vertical given that these were held constant across conditions.

Keywords: rotation direction, motion sickness, optokinetic drum.

THE MOST WELL-KNOWN theories of motion sickness (MS) are based on sensory conflict (9,11,12). In general, these theories assert that when afferent signals regarding self-motion are not in agreement, MS can result. Recently, a version of sensory conflict theory has been proposed by Bles and colleagues that asserts that intersensory conflicts in general do not cause MS, but rather only differences between sensed and expected gravitational verticals (1,4). 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.

It is well known that MS symptoms can occur in an optokinetic drum (3,5,7,8,10,13,14). Under optokinetic drum conditions a stationary subject inside a large rotating cylinder simply views the drum's interior. After several minutes MS symptoms often result. Bos et al. (4) have asserted that not all optokinetic drum conditions yield MS. These conditions are: 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. It has been suggested that MS symptoms are rare (except for dizziness) under these conditions (4). Such findings, except for the dizziness that is a known MS symptom, support the vertical mismatch theory because such optokinetic drum stimuli do not result in a subjective vertical mismatch. That is, under these conditions, sensed and expected gravitational verticals are in agreement.

When an optokinetic drum is tilted, the subjective vertical mismatch theory clearly asserts that the onset of MS should be hastened (4), and this has been shown to be the case compared with a drum that rotates around an Earth vertical axis (5). It is reasonable to assume that subjects' perceptions of verticality are influenced by the orientation of a striped pattern. Because the drum constitutes a large surrounding perceptual frame, there is a tendency to perceive it as vertical even when it is in fact tilted relative to gravity, much like the frame in the well-known rod and frame effect (6). However, the vestibular system will indicate that the subject is positioned vertically relative to Earth's gravity. Therefore, in a tilted drum there is a conflict regarding sensed and expected gravitational verticals, and as the subjective vertical mismatch theory would assert (1,4), MS onset is hastened in a tilted optokinetic drum.

However, hastened onset of MS in a tilted drum can also be explained in terms of a conflict regarding sensed and expected passive self-motion. Subjects in a tilted optokinetic drum report perceptions of tilting or swaying in addition to rotating. Inconsistent with these perceptions of swaying is the subject's vestibular input that indicates the subject is stationary. Exposure to a tilted optokinetic drum can result in a vertical mismatch, but also a mismatch regarding sensed and expected effects of passive motion; both types of conflicts occur simultaneously, making it impossible to tease out the effects of vertical mismatch and a mismatch regarding sensed and expected passive self-motion.

In the current study sensed and expected gravitational verticals did not change across conditions. Subjects' heads were centered on an Earth vertical axis and the drum always rotated on the same Earth vertical

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axis. In this way, mismatches regarding sensed and expected gravitational verticals were avoided. In an attempt to manipulate the degree of conflict regarding sensed and expected effects of passive motion, drum rotation direction either stayed the same or was changed every 30 s. The authors predicted that MS would develop earlier and be more severe when drum rotation was reversed every 30 s. Such a result would suggest that an intersensory conflict regarding sensed and expected effects of passive motion alone can lead to MS in the absence of a conflict regarding sensed and expected gravitational verticals.

METHODS

Subjects

There were 12 Saint Peter's College undergraduate students and faculty members who voluntarily participated in the experiment (4 men, 8 women). The age of the subjects ranged from 20 to 44 yr (mean = 24.4 yr). Persons reporting any visual, vestibular, neurological, or gastrointestinal abnormality, or any other health problem, were not allowed to participate. Subjects fasted for at least 2 h before each trial. The study was approved in advance by the Saint Peter's College Institutional Review Board. 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 wooden 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 approximately 2 s of rotation. 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 drum's interior. Illumination was provided by two 32-W florescent bulbs positioned directly behind a translucent plastic diffuser panel and 102 cm directly 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 approximately 30° of visual angle. The black and white stripes had luminance values of 1.6 and 36.0 $cd \cdot m^{-2}$, respectively.

Assessment Scales

Two subjective rating scales were used to assess MS. One scale was a 0–10 overall well-being scale (0 = I feel fine, 10 = I feel awful as if I am about to vomit). Data analysis was not performed on the overall well-being scores; instead these scores were used to comply with the approved human subjects protocol. For the purpose of providing data for analysis, a more specific subjective symptoms of motion sickness (SSMS) scale established in previous studies (3,5) was used to assess eight known MS symptoms. Each symptom was rated by the subject using a 0–3 scale (0 = none, 1 = mild, 2 = moderate, 3 = severe). The symptoms rated were spinning (described as vertigo), dizziness, bodily warmth, headache, increased salivation, stomach awareness, nausea, and dry mouth. These symptoms are commonly assessed on instruments designed by other MS researchers.

Procedure and Design

The subject sat inside the stationary drum and was familiarized with the overall well-being and SSMS scales. Baseline ratings were obtained at the beginning of each trial. The subject was instructed to close his/her eyes and the motor was turned on until the drum steadily rotated at a speed of $30° \cdot s^{-1}$ (5 rpm). For the first 30 s of each trial the subject viewed the drum as it rotated clockwise. In the same direction and different direction conditions the subject was then instructed to close his/her eyes and the motor was turned off, subsequently stopping drum rotation. The motor was then turned on again causing the drum to rotate either in the same direction (same direction condition) or the opposite direction (different direction condition). After a second viewing interval of 30 s the subject was again instructed to close his/her eyes for a 5-s period. This cycle was repeated in the same direction condition and the different direction conditions until the end of each trial, resulting in a sequence of 30-s periods of drum viewing separated by 5 s of eyes closed. The only difference was whether drum rotation alternately changed or remained the same throughout a trial. In the control condition, the subject was instructed to simply view the interior of a steadily rotating drum. Overall well-being and SSMS ratings were obtained after every 2 min of drum viewing throughout the trial. A trial concluded when the subject's overall well-being rating was a "5" or higher or 16 min of drum viewing had elapsed. Having no way of knowing at what interval data would be collected from all subjects, this procedure was followed in order to capture as much data as possible.

Each subject served in all three conditions: 1) same direction; 2) different direction; and 3) control (steady rotation). There were six possible orders of participation. Participation was completely counterbalanced to control for any possible order effects such as MS 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.

RESULTS

A SSMS composite score for the 2-min and 4-min intervals was calculated for each subject by adding the subjective ratings (0–3) for each of the eight symptoms probed. Although eight symptoms were probed, realis-

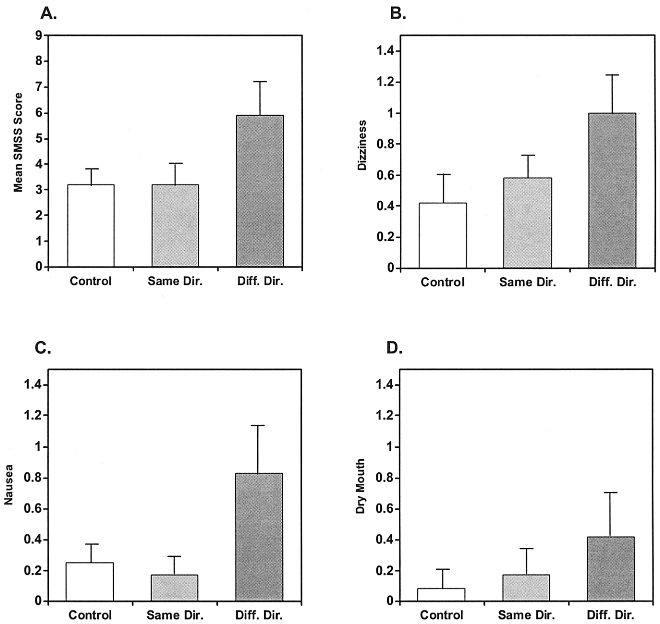

Fig. 1. A) Mean composite SSMS scores obtained for the 2-min interval, and mean subjective ratings obtained for B) dizziness, C) nausea, and D) dry mouth. Error bars represent the standard error.

tically, the highest possible score was a "21" because it was not possible for a subject to experience increased salivation and dry mouth at the same time. During MS onset, some individuals may experience increased salivation whereas other individuals may experience dry mouth.

The mean SSMS composite scores plotted for the 2-min interval are shown in **Fig. 1A**. At the 2-min interval, the mean SSMS composite scores in the control, same direction, and different direction conditions were 3.2, 3.2, and 5.9, respectively. A 1-way repeated measures ANOVA revealed a significant effect among conditions [F (2,22) = 5.2, $p < 0.013$]. A Tukey HSD post hoc analysis indicated that the mean SSMS composite scores in the control condition and the same direction condition were significantly lower than the mean SSMS score obtained in the different direction condition ($p < 0.05$).

Although the SSMS composite scores provide an overall indication of MS, all symptoms probed were not equally affected. Separate ANOVAs were conducted for each of the eight symptoms probed at the 2-min interval. Two symptoms were significantly affected by the experimental treatment: dizziness and nausea. The means obtained for dizziness were 0.42, 0.58, and 1.0, respectively, for the control, same direction, and different direction conditions (see **Fig. 1B**). A 1-way repeated measures ANOVA revealed a significant effect among conditions for dizziness [F (2,22) = 4.1, $p < 0.030$]. A Tukey HSD post hoc analysis indicated that the mean dizziness score obtained in the control condition was significantly different from the mean dizziness score obtained in the different direction condition ($p < 0.05$). The means obtained for nausea were 0.25, 0.17, and 0.83, respectively, for the control, same direction, and different direction conditions (see **Fig. 1C**). A 1-way repeated measures ANOVA revealed a significant effect among conditions for nausea [F (2,22) = 4.3, $p < 0.027$]. A Tukey HSD post hoc analysis indicated that the mean nausea score obtained in the same direction condition was significantly different from the mean nausea score obtained in the different direction condition ($p < 0.05$). The means obtained for dry mouth were 0.08, 0.17, and 0.42, respectively, for the control, same direction, and different direction conditions (see **Fig. 1D**). Differences for dry mouth approached significance [F (2,22) = 3.0, $p < 0.07$].

One subject did not reach the 4-min interval in the changing direction condition. For the purpose of analyzing the data, the SSMS composite score obtained for this subject at the 2-min interval was used. This approach is conservative. If this subject had continued on, a higher SSMS composite score might have been reached at the 4-min interval. For the 4-min interval the mean SSMS scores in the control, same direction, and different direction conditions were 5.0, 5.8, and 8.3, respectively (see **Fig. 2A**). A 1-way repeated measures ANOVA revealed a significant effect among conditions [F (2,22) = 4.6, $p < 0.022$]. A Tukey HSD post hoc analysis indicated that the mean SSMS composite score obtained in the control condition was significantly different from the mean SSMS score obtained in the different direction condition ($p < 0.05$).

Separate ANOVAs conducted for specific symptoms probed at the 4-min interval indicated that stomach awareness and nausea were significantly affected by the experimental treatment. The means obtained for stomach awareness were 0.33, 0.58, and 1.25, respectively, for the control, same direction, and different direction conditions (see **Fig. 2B**). A significant effect among conditions for stomach awareness was revealed [F (2,22) = 6.0, $p < 0.009$]. A Tukey HSD post hoc analysis indicated that the mean stomach awareness score obtained in the control condition was significantly lower than the

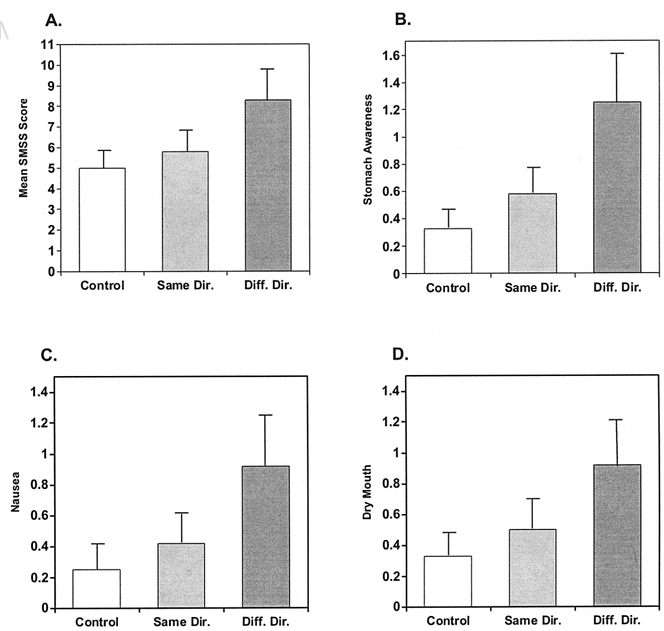

Fig. 2. A) Mean composite SSMS scores obtained for the 4-min interval, and mean subjective ratings obtained for B) stomach awareness, C) nausea, and D) dry mouth. Error bars represent the standard error.

mean stomach awareness score obtained in the different direction condition ($p < 0.01$). The means obtained for nausea were 0.25, 0.42, and 0.92, respectively, for the control, same direction, and different direction conditions (see **Fig. 2C**). A significant effect among conditions was revealed for nausea [$F(2,22) = 4.5$, $p < 0.024$]. A Tukey HSD post hoc analysis indicated that the mean nausea score obtained in the control condition was significantly lower than the mean nausea score obtained in the different direction condition ($p < 0.05$). The means obtained for dry mouth were 0.33, 0.50, and 0.92, respectively, for the control, same direction, and different direction conditions (see **Fig. 2D**). Differences for dry mouth approached significance [$F(2,22) = 3.0$, $p < 0.07$].

Analyzing SSMS scores at later-minute intervals did not seem prudent given that some subjects, having reported an overall well-being score of "5" or higher, were no longer allowed to continue in the experiment because of human subjects protocol approved by the college's Institutional Review Board. For example, only 9 subjects (75%) reached the 6-min mark in the different direction conditions whereas all 12 subjects reached the 6-min interval in the control and same direction conditions. Likewise, whereas data were collected for only 6 subjects (50%) at the 8-min interval, 11 subjects reached the 8-min interval in the control condition and 9 reached that interval in the same direction condition. Plotting data obtained beyond the 4-min interval would yield converging curves that at first glance would incorrectly seem to indicate that MS symptoms leveled off as later-minute intervals were reached. It seems reasonable to assume that had those subjects who dropped out of the experiment continued, their symptoms would have worsened.

DISCUSSION

Collectively, these results indicate that intermittently changing optokinetic drum rotation direction significantly hastens the onset of MS symptoms. The mean SSMS composite score obtained at the 2-min interval in the different direction condition (5.9) was 84% higher than the mean composite scores obtained in the control (3.2) and same direction (3.2) conditions. The optokinetic drum used in this study was rigid and rotated steadily on an Earth vertical axis. Subjects' heads were carefully aligned with the axis of rotation. It seems unlikely that a mismatch regarding sensed and expected gravitational verticals could have taken place under these experimental conditions. Instead, these results suggest that a mismatch between sensed and expected passive motion alone can lead to MS.

How exactly is this passive motion mismatch produced? Consider what sensed and expected passive motion would be in a steadily rotating drum. There is no passive motion sensed via vestibular stimulation when the subject's head is immobilized, but the visual system will indicate that passive rotation is occurring. As vection becomes steadier, as opposed to accelerating, vestibular stimulation should be the same as if actual passive rotation were occurring. Logic dictates that if sensory inputs are the same, resulting perceptions should also be the same. It is well known that vection is often not a steady state. However, the perception of passive rotation during actual physical steady rotation may not yield a steady perception of passive rotation either. Sensory conflict, although not eliminated entirely because of retinal slip, should be reduced during steady passive rotation on an Earth vertical axis regardless of whether the self-rotation is actual (physical) or perceived. There should be some sensory conflict with steady drum rotation and this would account for the MS symptoms that occurred in the control condition.

In the same direction condition one might predict more mismatch between actual and expected vestibular inputs. This is because subjects were instructed to close their eyes for 5 s after every 30 s of drum viewing. It seems reasonable to assume that when a subject closes their eyes in an optokinetic drum, vection decelerates. When the subject opens his/her eyes and views the drum rotating in the same direction as before, it is probably not the case that vection must start over again. A period of vection acceleration may take place, but it will not be as long as when the trial first began (2). In terms of sensed and expected effects of passive motion, it is the different direction condition that should theoretically yield the largest degree of conflict.

Like the control and same direction conditions, at the beginning of a trial in the different direction condition, sensed and expected effects of passive motion are at odds. Also, like the other conditions, as a subject continues to view the drum, sensed and expected vestibular inputs regarding passive motion will increasingly come to be more alike. After 30 s, when the subject closes his/her eyes and then opens them to view the drum as it rotates in the opposite direction, the conflict regarding sensed and expected effects of passive self-rotation is renewed. In short, the sensed effects of passive motion on the vestibular system remain the same, but the expected effect changes every 30 s. The result is a frequently renewed sensed/expected mismatch related to passive self-motion that results in an accelerated onset on MS in the different direction condition.

One could argue that even though an optical chin rest was used to position subjects' heads, slight head movements occurred when verbal responses were given. These head movements could have resulted in pseudo Coriolis effects that subsequently led to MS. However, given that the drum rotated on the same Earth vertical axis in all three conditions, and that the amount of verbal responding was essentially the same in all conditions, it seems unlikely that head movements could account for the differences that were obtained.

Another potential criticism of these results is that comparisons between the control condition and the other two conditions are unfair. Statistical analyses were conducted for comparable intervals of "drum viewing," not time spent in the drum. For example, at the 2-min interval when SSMS ratings are recorded, although subjects in the control condition were in the drum for 2 min, subjects in the same direction and different direction conditions were in the drum for 2 min and 15 s. The extra 15 s is accounted for by the periods during which subjects have their eyes closed. One could argue that even during closed-eyes periods MS symptoms continued to develop. However, at the 2-min interval the mean composite SSMS score obtained in the same direction condition was significantly lower than the mean SSMS composite score obtained in the different direction condition. For these two conditions, the time spent viewing and in the drums was exactly the same.

In summary, these results suggest that mismatches between sensed and expected passive motion alone can lead to MS. We acknowledge the possibility that the differences revealed in the current experiment could have been due to direction specific adaptation, a concept that will be tested in future research. However, in the current experiment, sensed and expected gravitational verticals were the same in all three conditions. It then follows that the results of this experiment cannot be accounted for with the subjective vertical mismatch theory of MS (1,4). Given that virtually all cases of vertical mismatch in either real or perceived passive motion environments also result in a conflict regarding sensed and expected passive motion, here we suggest that the latter may be the provocative stimulus for MS and not the former.

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