Cybersickness without the wobble: experimental results speak against postural instability theory

Mark Stephen Dennison 1*, Michael D'Zmura 1

[1]Cognitive NeuroSystems Laboratory, University of California, Irvine, Department of Cognitive Sciences, Irvine, CA, USA

***Correspondence:** Mark Dennison, Cognitive NeuroSystems Laboratory, University of California, Irvine, Department of Cognitive Sciences, 2201 Social & Behavioral Sciences Gateway Building, Irvine, CA 92697-5100, USA

mdenniso@uci.edu

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Abstract

Stoffregen and Smart (1998) suggest that postural instability is needed for cybersickness to occur. We examine this notion in a replication of a study by Dichgans and colleagues (1972) using virtual reality technology. Seated and standing subjects used a head-mounted display to view a virtual tunnel that rotated about subjects' line of sight. We measured changes in their perceived vertical settings and in their posture. We found that the offset direction of perceived vertical settings matches the direction of the tunnel's rotation, so replicating earlier findings. Increasing the speed of rotation caused cybersickness to increase, but had no significant impact on perceived vertical settings. For each subject, postural sway during virtual environment rotation was similar to postural sway during resting baseline. While a minority of subjects exhibited postural sway in response to the onset of virtual environment rotation, the majority did not. Furthermore, cybersickness ratings increased with rotation speed similarly for the seated and standing viewing conditions. Finally, subjects with greater levels of cybersickness exhibited less variation in postural sway. These results lead us to conclude that the link between postural instability and cybersickness is a weak one in the present experiment.

1 Introduction

Dichgans and colleagues (1972) found that the perceived direction of gravity depends on the motion occurring in the observer's visual field. For rotations about the line of sight, they found that the perceived vertical direction tilts in the direction of visual stimulus rotation and that this tilt increases with rotation speed. Earlier work found that seated individuals who viewed a tilted room felt an illusory self-tilt about body roll or pitch axes (Kleint 1936; Witkin and Asch 1948; Asch and Witkin 1992). Howard and Childerson (1994) found that exposure of seated subjects to a rotating furnished tunnel produced the sensation of tumbling, and Allison and colleagues (1999) found that this sensation increased with field of view and tunnel rotation velocity.

In many individuals, this kind of vection is associated with visually induced motion sickness (VIMS). Vection is an illusory phenomenon which occurs when self-motion is felt by a stationary observer. The classic example of vection is the feeling of moving backwards in a stopped train while train cars alongside you pull forward, creating the illusion of self-motion in the backwards direction (Helmholtz 1896). This perception occurs when the visual and vestibular systems receive information that are in conflict (Hu et al. 1991).

VIMS symptoms include drowsiness, dizziness, fatigue, pallor, cold sweat, oculomotor disturbances, nausea, and vomiting (Graybiel and Miller 1974). The underlying causes of VIMS are still not agreed upon, but two prominent theories exist: sensory rearrangement theory and postural instability theory (LaViola 2000). Sensory rearrangement theory poses that sickness is caused when visual, proprioceptive, and vestibular signals do not match up with a person's expected sensations (Money and Myles 1975; Reason and Brand 1975).

Postural instability theory is centered on the idea that maintaining stability of the body is critical and that prolonged instability may lead to VIMS (Riccio and Stoffregen 1991). For example, if a stationary subject views a rotating tunnel, then vection from the perceived motion of the rotating tunnel is uncorrelated with the motions necessary to maintain balance. Stoffregen and Smart (1998) claim that postural instability is a prerequisite for VIMS to occur. Although many studies support this claim (Stoffregen and Hettinger 2000; Smart, Stoffregen, and Bardy 2002; Flanagan, May, and Dobie 2004; Reed-Jones et al. 2008; Villard and Flanagan 2008; Apthorp and Palmisano 2014), others have found that the relationship between postural stability and VIMS is less clear (Häkkinen et al. 2002; Akizuki et al. 2005; Guerraz and Bronstein 2008; Wang, Kenyon, and Keshner 2010).

The relationship between vection and VIMS has been debated in the literature. While previous studies have found evidence that the strength of reported vection is positively correlated with the severity of VIMS (Hettinger et al. 1990; Lee, Yoo, and Jones 1997; Stoffregen and Smart 1998; Smart, Stoffregen, and Bardy 2002; Flanagan, May, and Dobie 2004; Bubka and Bonato 2006; Bonato, Bubka, and Palmisano 2008; Golding et al. 2009; Classen, Bewernitz, and Shechtman 2011; Diels and Howarth 2011; Keshavarz et al. 2014), others have found only weak or no correlation between vection magnitude and VIMS severity (Lawson 2001; Golding et al. 2012; Keshavarz and Hettinger 2014). For example, Fushiki (2009) exposed subjects to upward or downward moving random dot patterns and measured vection onset times and postural stability before, during, and after stimulus exposure. Postural sway was increased only after participants reported vection and became stronger after stimulus presentation than before.

The current experiment used a head-mounted display (HMD) to immerse subjects in a rotating VE to induce vection. Subjects' perception of vertical was recorded alongside measures of postural sway. Based on results by Dichgans and colleagues (1972), we hypothesized that the perceived vertical would be offset in the direction of VE rotation and that the magnitude of this offset would increase with rotation speed. We also hypothesized that our subjects would feel cybersickness, a type of VIMS felt during VE immersion, due to the sensory mismatch caused by stationary viewing of a virtual rotating stimulus and possibly by postural instability. We collected self-reports of cybersickness during VE immersion and simultaneously recorded changes in subjects' posture using a Wii balance board (Clark et al. 2010). A seated condition was used to test whether or not cybersickness would occur while subjects had postural stability.

Results show that our virtual stimulus produced data similar to that of Dichgans' physical monocular stimulus (Dichgans et al. 1972) and also produced cybersickness. Furthermore, perceived vertical settings did not differ significantly between seated and standing HMD use. Finally, changes in postural sway were associated with cybersickness in only a minority of subjects. These results demonstrate a weak link between postural instability and cybersickness.

2 Methods

Subjects wore an HMD and viewed a virtual tunnel that rotated clockwise or counter-clockwise about the line of sight at six different speeds from trial to trial. Subjects rotated a virtual arrow to indicate their perceived vertical and rated their level of cybersickness. In the first condition subjects sat comfortably in a chair. The second condition was administered on a second day; the same subjects stood on a Wii balance board so that changes in their postural sway could be measured while they were immersed in the VE.

2.1 Virtual environment and equipment

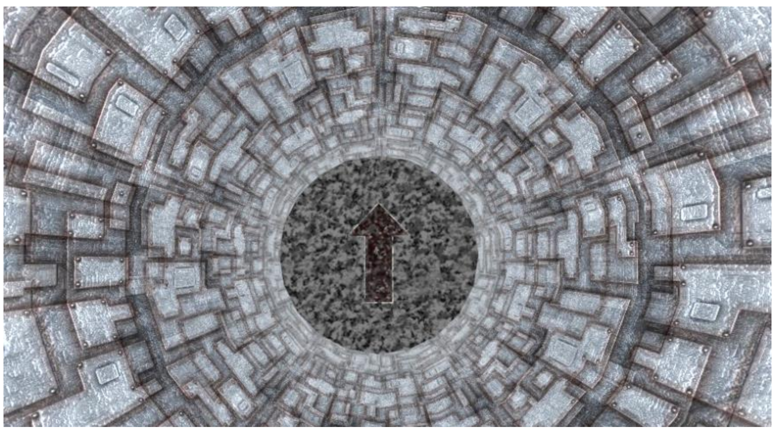

Fig 1. Screenshot of the VE used in seated and standing conditions. The tunnel rotated about a central disk upon which an arrow appeared intermittently for use in perceived vertical settings. The disk's texture was used to minimize the screen door effect reported by HMD users in a pilot study. Subjects used the analog stick on an Xbox controller to point the black arrow along the direction of their perceived vertical.

The VE was developed in the Unity 5 game engine and was deployed on a desktop PC. The VE included a cylindrical tunnel that rotated about the line of sight (see Fig 1). Subjects viewed the VE through an Oculus Rift (Oculus VR, Development Kit 2), which has a resolution of 960 x 1080 pixels per eye with a refresh rate of 75Hz. The field of view was 100 x 100 degrees of visual angle. Internal tracking of head rotations and translational movements occurred at 1KHz. Changes in posture were recorded with a Nintendo Wii balance board. Data from the Wii balance board and HMD were sampled at a rate of 100 Hz and sent wirelessly to a separate recording computer.

The central disk's texture was chosen to minimize the screen door effect that is sometimes visible in the HMD and which may provide orientation artifacts. The screen door effect occurs when an HMD wearer is able to shift their focus from the VE to the grid of pixels forming the actual display. Minimization of the screen door effect was important because a user who attends to the HMD's pixel array may be biased by the array orientation when making their perceived vertical settings.

2.2 Procedure

Subjects were first instructed how to use an Xbox controller in the experiment. Subjects sat comfortably in a chair in the seated condition. For the standing condition, subjects were instructed to place their feet on marked locations on a Wii balance board. The HMD was then placed over the subject's eyes and was adjusted until the image looked clear.

Before each block of trials, the subject was asked to fixate on the central disk and to remain still for 30 seconds. These data were used to measure the subjects' natural head position and, if standing, the distribution of weight across the feet. After the subject pressed a button on the controller, the walls of the virtual tunnel began to rotate clockwise or counter-clockwise at one of six fixed speeds for 15 seconds. The six speeds were 6, 17, 28, 38, 49, and 60 deg/sec. After fifteen seconds, a black arrow appeared at a random orientation on the central disk. The subject then had an additional 15 seconds to rotate the arrow to point up along their perceived vertical and to press a button. Subjects were allowed to change freely their perceived vertical selection within these 15 seconds, although few took advantage of this. After the trial ended, the screen turned to gray and subjects were given a text prompt to select how they felt on a sickness scale: 1 no symptoms; 2 mild symptoms, but no nausea; 3 mild nausea, and 4 moderate nausea (Bagshaw and Stott 1985). Subjects completed 8 blocks of 6 trials each for the seated and standing conditions. Subjects viewed every possible speed-direction combination four times for both seated and standing conditions. To ensure ease of response entry, when a subject pressed the response selection button, the color of the arrow changed to blue for confirmation and to red if the subject had not yet responded and only five seconds remained in the trial. Time to respond was also measured for each trial to assess whether or not user decision time was affected by stimulus rotation speed or direction.

Subjects were told that if at any time they felt too sick to continue the experiment, they were to inform the experimenter who would help them exit the VE immediately. Subjects who terminated the experiment early for this reason were asked to rest before leaving the laboratory. A single subject dropped out of the experiment because of cybersickness. This person felt too ill to continue after completing half of the trials in the standing condition. This person's data were not used. Subjects were recruited to come in on two separate days to run the seated and standing conditions of the experiment. This was done to ensure that any motion sickness that might have occurred during one experiment condition would be gone by the time of the second experiment.

2.3 Questionnaires

Subjects began the experiment by completing the Motion Sickness Susceptibility Questionnaire (MSSQ) (Golding 2006). The MSSQ assesses how susceptible a person is to motion sickness based on their past experience. It asks how often the subject felt nausea during different activities and is scored using a five point scale: 0 never, 1 rarely, 2 sometimes, 3 frequently, and 4 always.

The amount of time spent traveling in different types of vehicles is tallied and used for calculating the final susceptibility score (for more detail see Golding 2006).

Subjects filled out the Simulator Sickness Questionnaire (Kennedy and Lane 1993) after completing the experiment. The questionnaire contains a list of 16 symptoms that subjects rate on a 4 point scale: 0 absent, 1 slight, 2 moderate, and 3 severe. These ratings are tallied to create scores for three sickness subscales: Nausea, Oculomotor, and Disorientation. A total cybersickness score is then computed from these three subscales.

3 Analysis

3.1 Behavioral data

Perceived vertical settings, cybersickness ratings, and times to respond were grouped according to VE rotation speed and direction in seated and standing conditions for all subjects.

3.2 Wii and HMD data

The Wii balance board uses four sensors to record the user's weight. All postural sway measurements are reported as changes in weight distribution across these sensors. Data from the backward two sensors were summed and then subtracted from the sum of the forward two sensors' data to create a single Forward-Backward (FB) time series. Data from the left two sensors were summed and then subtracted from the sum of the right two sensors' data to create a single Right-Left (RL) time series. The means of the FB and RL time series from the resting period before each block were subtracted from all subsequent trials in that block to take into account the baseline posture.

Standard deviations in body posture and head position time series in the FB and RL directions were computed over the 30 sec baseline and trial periods. These were used to assess postural sway (Koslucher et al. 2012). We used *t*-tests for groups with unequal numbers of observations to assess differences in sway between stimulus trial and baseline periods.

Cross correlations were computed between the HMD position and balance board signals in the FB and RL directions on each trial for every subject (N = 13). These were computed to ensure that variations in body postural sway included movements of the head. The cross correlations used lags every 0.01 sec in the range -30 to 30 sec. We computed a 95% confidence interval at each of these lags by calculating the cross correlation between the HMD signal from one trial and the postural signal from an unmatched trial. This process was repeated individually for every subject to create a 1000 sample confidence distribution at each lag on every trial (Horton, D'Zmura, and Srinivasan 2013).

We wanted to see if postural and head position information at trial onset could be used to determine the direction of the stimulus rotation within individual subjects. First, we grouped all trials for the two fastest stimulus rotation speeds (49 and 60 deg/sec) according to rotation direction: CW or CCW. Second, we summed samples from the first second of data from each trial to get a direction index. FB data from trials that summed to a positive value show a shift in the forward direction, while FB data from trials that summed to a negative value show a shift in the backwards direction. We computed similar sums for RL data. Finally, we performed a two-tailed *t*-test between these two bins for CW and CCW trials for each subject.

We wanted to determine whether postural sway and head movement are associated with cybersickness. Subject data were first divided into two groups. Those subjects with an SSQ cybersickness score greater than the median score were placed into the "less comfortable" group, while the remaining subjects were placed into the "more comfortable" group. Second, we grouped all trials for the two fastest stimulus rotation speeds (49 and 60 deg/sec) according to rotation direction: CW or CCW. We selected these trials because the motion sickness ratings at these two speeds were correlated with end-of-experiment SSQ cybersickness scores. Finally, we performed a two-tailed *t*-test to assess any difference between the FB variability in trials for the less comfortable subjects and variability in trials for the more comfortable subjects. Variability for each trial was defined as the standard deviation in FB postural sway (e.g., Koslucher et al. 2012).

3.3 Participants

Fifteen subjects (4 F, 11 M) over the age of 18 participated in the study. Informed consent was obtained prior to the experiment in accordance with protocol HS# 2014-1090, approved by the Institutional Review Board at UC Irvine. All participants indicated that they had previous experience playing video games on a wide screen display. None of the participants reported any vestibular or neurological dysfunction.

4 Results

4.1 Questionnaires

The MSSQ assesses how susceptible a person is to motion sickness based on their past experiences as a child and over the past ten years. The subject-averaged MSSQ total score was 22.9 (sd = 20.07), which indicates that our subjects are amongst the 30th percentile, which is a lower-than-average susceptibility (Golding 1998).

The SSQ was used to assess cybersickness symptoms immediately at the ends of both seated and standing conditions. It provides nausea, oculomotor discomfort, disorientation, and total sickness scores. For the seated condition, the subject-averaged SSQ score for nausea was 15.9 (sd = 17.7), for oculomotor discomfort was 19.20 (sd = 18.31), for disorientation was 24.13 (sd = 27.01), and for cybersickness was 22.19 (sd = 20.46). For the standing condition, the subject-averaged SSQ score for nausea was 34.34 (sd = 39.79), for oculomotor discomfort was 17.18 (sd = 19.53), for disorientation was 22.27 (sd = 37.13), and for cybersickness was 27.93 (sd = 33.27). A paired samples *t*-test determined that SSQ scores did not differ significantly between the seated and standing conditions. Significant correlations were found in the seated condition between the MSSQ total score for susceptibility and SSQ subscale scores for nausea, $r = .522$, $p = .046$, oculomotor discomfort, $r = .657$, $p = .008$, disorientation, $r = .572$, $p = .026$, and cybersickness, $r = .665$, $p = .007$.

We used the variability in subjects' SSQ cybersickness scores to create two post-hoc subject groups: more comfortable and less comfortable (see Section 3.2). The seven subjects whose score was less than the median SSQ cybersickness score of 18.7 were placed into the "more comfortable" group and the remaining subjects were placed into the "less comfortable" group.

4.2 Behavioral measures

We ran three 2x6x2 mixed-design ANOVAs to compare the effects of VE rotation in two directions and at six angular velocities on subject estimates of perceived vertical, on cybersickness ratings, and on times to respond.

4.2.1 Perceived vertical settings

There was a significant main effect of direction on perceived vertical settings, $F(1, 13) = 50.439$, $p < .000$, and a near significant main effect of speed, $F(5, 65) = 2.296$, $p = .055$ (see Fig 2). There was a three-way interaction between condition, direction, and speed, $F(5,65) = 2.571$, $p = .035$. Follow-up comparisons found that this effect was driven by the difference between rotation speeds 17 and 60 deg/sec. These results show that the perceived vertical offset directions match the direction of stimulus rotation in the seated and standing conditions, which agrees with the original result of Dichgans and colleagues (1972). Yet the perceived vertical offsets did not increase as stimulus rotation speed was increased, a discrepancy discussed in Section 5.

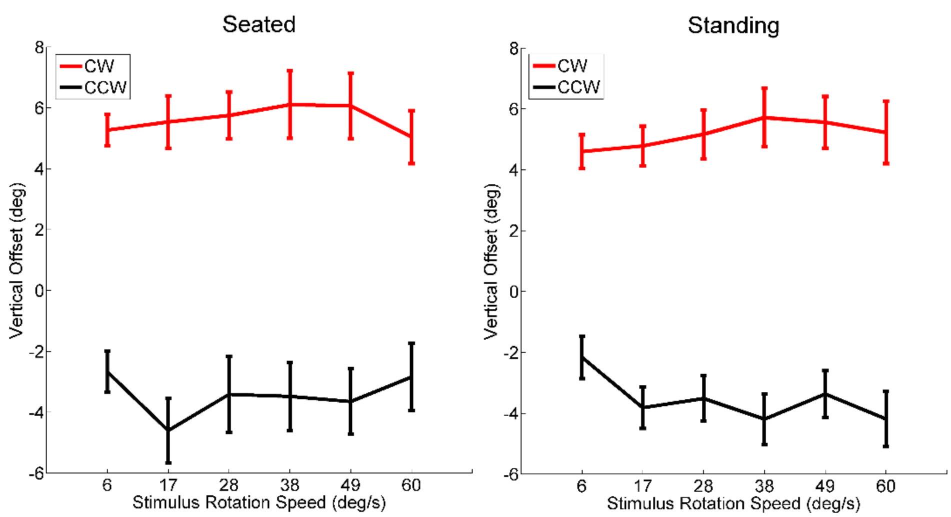

Fig 2. Plot of perceived vertical settings for the different stimulus rotation speeds during the seated (left panel) and standing (right panel) conditions. Subject- and trial-averaged data from clockwise (CW) trials are shown in red and from counterclockwise (CCW) trials are shown in black. Subjects' perceived vertical settings followed the stimulus rotation direction, but did not increase with speed.

4.2.2 Cybersickness ratings

There was a significant main effect of tunnel rotation speed on cybersickness ratings, $F(1.346,17.494) = 5.051$, $p = .029$ (see Fig 3). One might expect postural instability to be greater for standing than for seated subjects and, according to postural instability theory, for cybersickness ratings to increase more for standing than for seated subjects. The results do not support this expectation. We correlated the SSQ results for seated and standing conditions with the cybersickness ratings for those conditions at each stimulus rotation speed. We found that SSQ cybersickness scores are positively correlated with cybersickness ratings during the standing condition for the two fastest CW rotations (49 deg/sec CW, $r = .674$, $p = .008$, for 60 deg/sec CW, $r = .828$, $p = .000$) and for the two fastest CCW rotations (49 deg/sec CCW, $r = .598$, $p = .024$, and 60 deg/sec CCW, $r = .738$, $p = .003$). The increase in cybersickness with rotation speed shown here in Fig 3 is not accompanied by change in perceived vertical settings (see Fig 2). This shows that perceived vertical settings and cybersickness ratings are not correlated in this experiment.

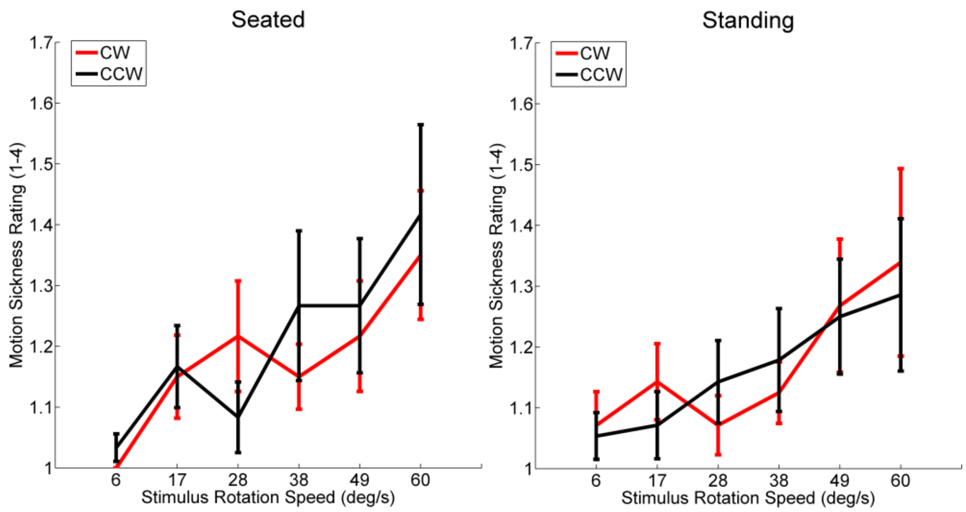

Fig 3. Plot of motion sickness ratings for the different stimulus rotation speeds during the seated (left panel) and standing (right panel) conditions. Subject- and trial-averaged data from clockwise (CW) trials are shown in red and from counterclockwise (CCW) trials are shown in black. Motion sickness ratings increase with speed similarly for both the seated and standing conditions.

4.2.3 Times to respond

Subjects viewed the rotating stimulus on each trial for 15 seconds before the arrow appeared, at which time they could make their perceived vertical setting. Times to respond show that subjects made the setting after the arrow was visible for five seconds on average. However, the time that subjects took to respond did not differ significantly for stimulus speed, direction, or experimental condition.

4.3 Postural data analyses

We analyzed changes in posture to test whether postural instability theory is consistent with results. HMD data from one subject and HMD and posture data from another subject were unavailable due to signal loss in the recording.

4.3.1 Body and head variation in baseline and trial periods

We used standard deviations of FB and RL samples to measure postural sway (see Fig 4). Standard deviations were computed for each subject for each trial (four left bars in each panel) and for each subject's baseline period (four right bars in each panel). Postural sway magnitude differed across subjects. Some subjects showed very small changes in head and body positions (e.g., S14), and others showed substantially larger changes (e.g., S1). For each subject, 48 standard deviations were found for the trial periods: one standard deviation per trial. For each subject, 8 standard deviations were found for the baseline periods: one standard deviation per baseline. These multiple measurements let us compute standard errors of the mean (displayed as error bars in Fig 4) and to assess differences in postural sway between virtual environment rotation and resting baseline periods using *t*-tests for unequal number of observations. Postural sway was significantly greater during stimulus rotation in the FB direction for S3, $t(54) = 2.30$, $p < .05$, and in the RL direction for S1, $t(54) = 1.78$, $p < .05$. For data averaged across fourteen subjects, we found no statistically significant differences in head or body sway in either direction between stimulus rotation and baseline periods.

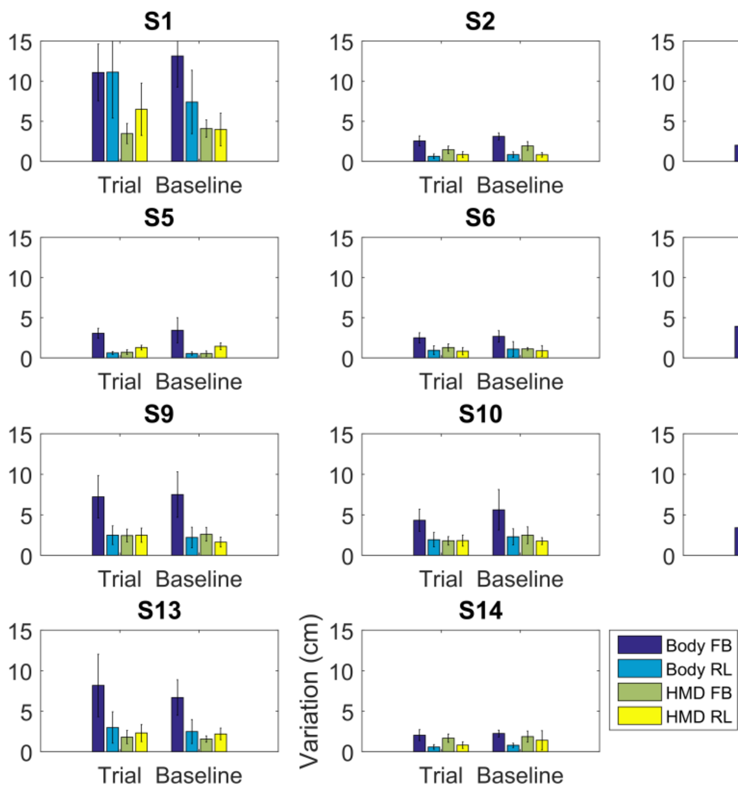

Fig 4. Comparison of pre-trial baseline and within-trial variation in body posture (FB, dark blue; RL light blue) and head position (FB, green; RL yellow) for 14 subjects. Variation for head position is in units of cm and variation for body posture is in units of kg. Variation during stimulus exposure was similar to variation during the baseline periods. Data show that some individuals had greater overall variation in their body posture and head position. Error bars show the standard error of the mean for 48 trials and for 8 baseline periods.

4.3.2 Head and body movement correlation

Cross correlations were computed between HMD position data and Wii board posture data for all trials for each subject to examine the relationship between head position and postural sway (see Fig 5). The subject-average peak correlation in the FB direction was 0.745 (sd = 0.13) at a lag of 25 ms (sd = 42.74). This peak was significantly above the 95% confidence interval for 11 of the 13 subjects. The subject-average peak correlation in the RL direction was 0.704 (sd = 0.14) at a lag of 63.077 ms (sd = 178.16). This peak was significantly above the 95% confidence interval for only two of the 13 subjects. The results for the FB direction show that changes in head position and body posture are closely coupled, with body posture changes associated with near-immediate changes in head position. This is not the case for the RL direction. RL movements of the head and body on different trials are more correlated than the average found for head and body movements on identical trials (see Fig 5 lower-right panel).

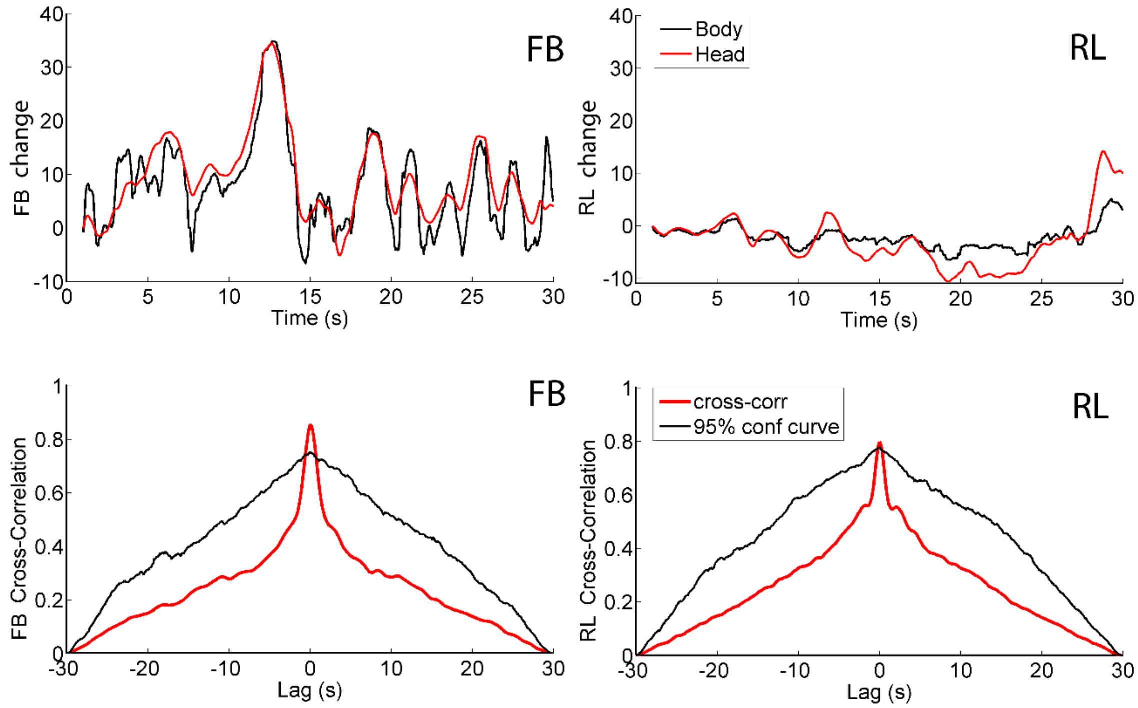

Fig 5. Top panels: Raw body posture (black line) and head position (Red line) data from a representative subject in the FB (top-left) and RL (top-right) directions. Change for the HMD data are in units of (scaled) cm while change for the posture data are in units of kg. HMD data in the upper plots are scaled by a factor of twenty to enhance visual comparison. Bottom panels: trial-averaged cross correlations between head and body movements in the FB (bottom-left) and RL (bottom-right) directions. The red lines in the bottom panels show the mean cross correlations over all trials. The black lines in the lower panels show the 95% confidence intervals from correlations between head and body on unmatched trials. Each cross correlation used lags separated by 0.01s from -30 to 30 sec. A clear peak in correlation is seen at lag zero sec, which demonstrates that FB movement in the body and head are closely related. Cross-correlations found for head and body data from the same trial in the RL direction did not exceed those generated when using head and body data from different trials

4.3.3 Stimulus evoked postural change

Only three subjects showed significant differences between their CW and CCW FB postural data immediately after stimulus onset. The remaining 12 did not exhibit these differences. Data from a representative subject who showed these differences are displayed in Fig 6. Plots of data for a representative subject who did not show these differences are shown in Fig 7. Identical scales are used in Figs 6 and 7 for purposes of comparison. Data from the majority of subjects resembled those shown in Figure 7. There was no significant shift in FB posture at stimulus onset for the majority of subjects, which suggests that postural instability is not a prerequisite of cybersickness in this experiment. No subjects showed significant differences between their CW and CCW FB head position data during the first second after stimulus onset.

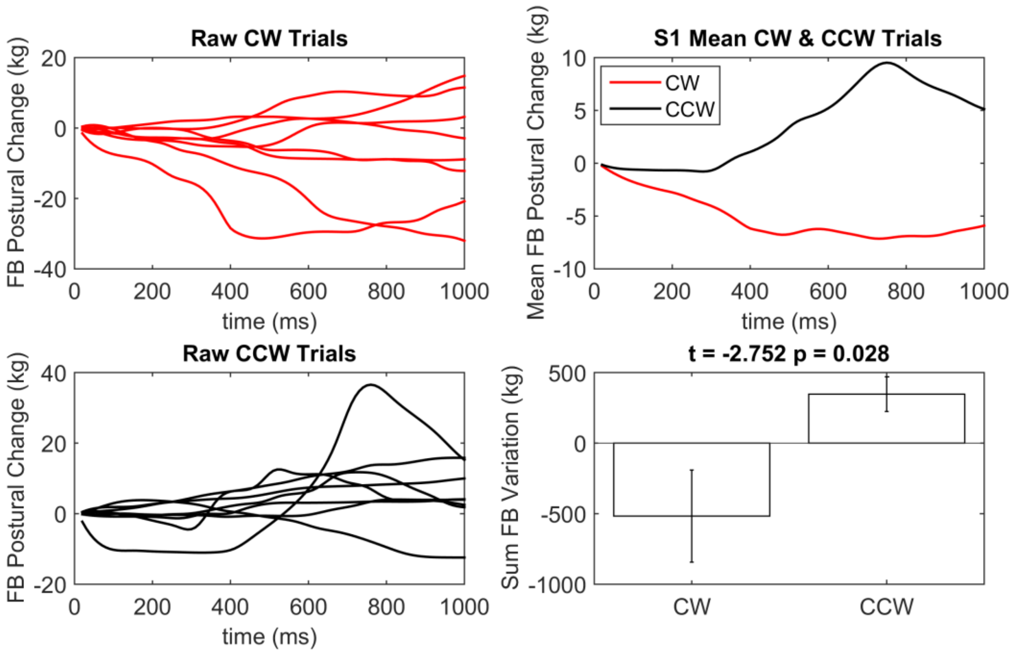

Fig 6. Postural change data from a subject from the minority who show a significant change in posture in response to stimulus rotation onset. The upper-left panel shows the FB postural change during viewing of CW stimuli rotating at the two fastest speeds (49 and 60 deg/sec) (red lines). The lower-left panel shows the FB postural change during viewing of CCW stimuli rotating at 49 and 60 deg/sec (black lines). The upper-right panel shows the mean FB postural changes during CW and CCW stimulus viewing. The lower-right panel shows the significant difference between the distribution for summed CW trial FB postural change and CCW postural change.

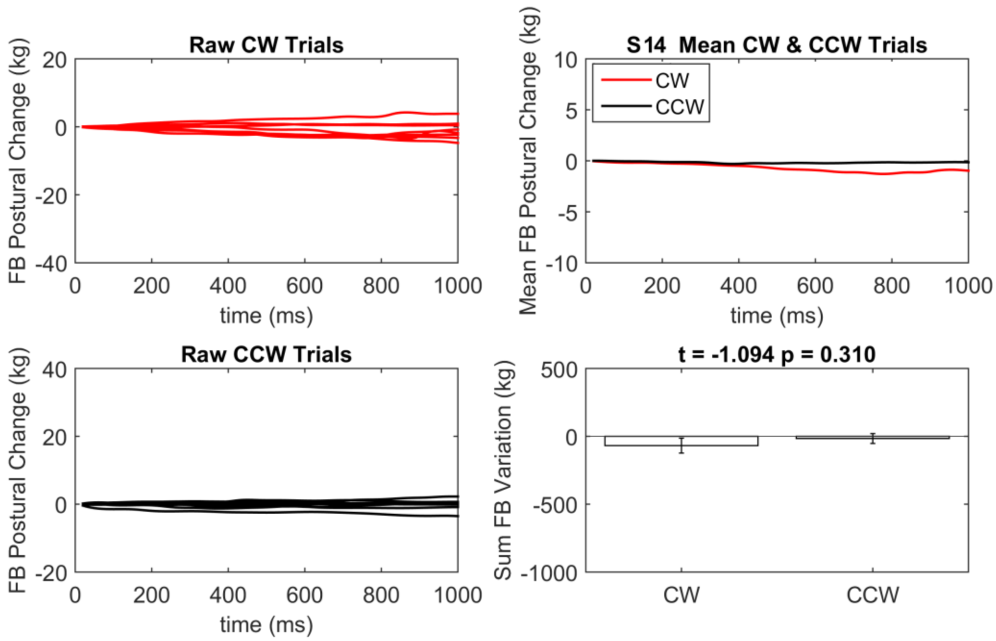

Fig 7. Postural change data from a subject from the majority who do not show a change in posture in response to stimulus rotation onset. The scales in these plots are identical to the scales used in the plots of Fig 7. The upper-left panel shows the FB postural change during viewing of CW stimuli rotating at the two fastest speeds (red lines). The lower-left panel shows the FB postural change during viewing of CCW stimuli rotating at 49 and 60 deg/sec (black lines). The upper-right panel shows the mean FB postural changes during CW and CCW stimulus viewing. The lower-right panel shows that the distribution for summed CW trial FB postural change and CCW postural change are not significantly different.

4.3.4 FB and RL variation across trials

FB postural sway was significantly lower for the less comfortable subjects than for the more comfortable subjects (see section 3.2), $t(111) = -2.3$, $p = .023$ (see Fig 8). This result is not what one would expect were postural instability theory correct. Neither RL postural sway nor head position differed significantly between less comfortable and more comfortable subjects.

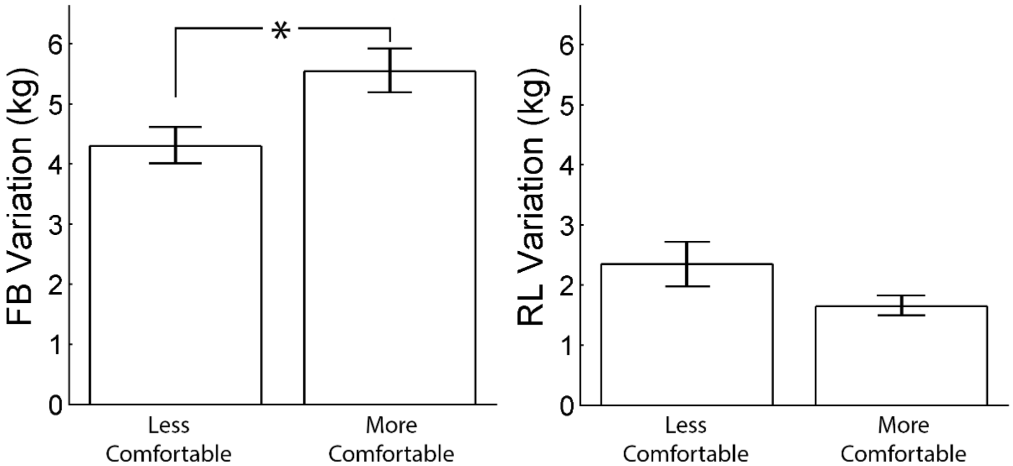

Fig 8. Subject-averaged postural variation over all trials at stimulus speeds of 49 and 60 deg/sec in the FB direction (left plot) and RL direction (right plot). The data show that the less comfortable subjects had significantly less (t = -2.3, p = .023) FB variation than the more comfortable subjects. There was no significant difference between subject groups for variation in the RL direction. Error bars show the standard error of the mean for 14 subjects.

5 Discussion

Results from this experiment show that cybersickness can occur in the absence of postural instability. We replicated the study of Dichgans and colleagues (1972) using virtual reality technology with the expectation that both cybersickness and postural sway would increase with rotation speed. We did not find this result. Instead, our results with perceived vertical settings, response times, balance board postures, and cybersickness ratings show that cybersickness increased without appreciable postural sway in the majority of subjects (see Figs 3, 7, and 8).

Dichgans and colleagues (1972) found that the perception of vertical is influenced by a visual environment that rotates about the line of sight. Our results follow theirs in showing that the perceived vertical direction is offset in the direction of the visual environment’s rotation. Yet, we failed to replicate the strong increase in perceived vertical offset with stimulus rotation speed. Average peak offsets in the present study were about six degrees but reached 15 degrees in the original Dichgans study. This may be due in part to the fact that they used a larger visual field: 130 vs 100 deg. The original results lead us to believe that our choice of 60 deg/sec was fast enough to elicit a maximum offset in the perceived vertical direction. The difference in results may also be due to different methods of stimulus presentation. Dichgans and colleagues (1972) had subjects view the rotating stimulus monocularly and increased its speed every 30 seconds over a six minute period. It may have been the case that rotatory motion aftereffects of earlier stimuli influenced later settings (e.g., Freud 1963). Our experiment interleaved changes in rotation direction and speed from trial to trial. We found no significant variation in the times subjects took to respond, and feel it is unlikely that aftereffects from previous trials played a substantial role in perceived vertical estimates.

Cybersickness ratings were found to increase with rotation speed. This may be caused by vection that is induced by viewing the stimulus rotation. A positive relationship between vection strength and VIMS strength is well documented in the literature (Hettinger et al. 1990; Stoffregen and Smart 1998; Flanagan, May, and Dobie 2004; Golding et al. 2009; Diels and Howarth 2011; Lee, Yoo, and Jones 1997; Smart, Stoffregen, and Bardy 2002; Bubka and Bonato 2006; Bonato, Bubka, and Palmisano 2008; Classen, Bewernitz, and Shechtman 2011; Keshavarz et al. 2014). However, a weakness of our design is that we did not explicitly ask subjects to rate their level of vection. In fact, our data show that only perceived vertical direction was influenced significantly by the stimulus and perceived vertical offset magnitude was not. This suggests that the relationship between vection strength and perceived vertical differs from the relationship between vection strength and cybersickness. It may be possible for individuals to become habituated to any vection produced by the stimulus, yet still feel cybersickness. Diels and Howarth (2011) exposed subjects to a rotating cloud of dots and found that although subjects reported feeling some VIMS symptoms, vection incidence actually decreased momentarily as sickness increased steadily. VIMS in the absence of vection was also found by Ji and colleagues (2009).

Our data show that sickness ratings increase with speed similarly during the seated and standing conditions, with some subjects reporting nausea (sickness rating 3). It may be that proprioceptive information felt from being seated in a chair or information from shifts in postural sway while standing on the balance board contributed little to estimation of perceived vertical. The visual information provided by the HMD was so compelling that it outweighed information provided by proprioception and gravity. Past work has found that visual information in many scenarios trumps conflicting information from the other senses (e.g., Slutsky and Recanzone 2001; Recanzone 2009).

Motion sickness ratings at the two fastest rotation speeds were significantly correlated with the end-of-experiment SSQ cybersickness scores. This is interesting because trials at the two fastest speeds were interleaved throughout the experiment. Those individuals who felt cybersickness during these trials likely have a lower threshold for cybersickness and ultimately reported feeling worse at the end of the experiment.

Postural stability measures did not correlate with SSQ scores for individual subjects. Cobb (1999) found that self-reported symptoms of postural instability were correlated with simulator sickness in a VE, but that post-immersion SSQ scores and post-immersion postural stability measures were not. This suggests that a user’s subjective sense of discomfort may be a better measure of cybersickness than their objective postural stability. This suggestion is strengthened in the present experiment by the fact that there was little difference in the variation of body posture and head position between the data from stimulus rotation and resting baseline periods (see Fig 4). Our stimulus paradigm was strong enough to produce cybersickness, but was likely too weak to elicit significant changes in postural stability. The maintenance of postural stability in the current experiment may be related to the briefer exposure times to stimulus rotation. Kennedy and colleagues (1995) suggest that exposure to VEs for less than three hours will not induce postural instability.

Separating subjects by median SSQ score showed that less comfortable subjects had less FB variation in postural sway than more comfortable subjects during trials at the two fastest rotation speeds (see Fig 8). Subjects with less FB sway felt worse than subjects with more. It may well be that the majority of subjects exhibited “VR lock” during which they minimized motion in an attempt to avoid cybersickness. Subjects who maintained fluid body motion reported less post-experiment cybersickness. On average, the less comfortable subjects showed greater RL variation than the more comfortable subjects, but this trend was insignificant. While we were initially surprised by greater levels of postural sway along the FB than along the RL direction (see Figs 4 and 8), earlier studies have reported similar findings (e.g., Koslucher et al. 2012).

The cross-correlation results show that movements of the head were closely related to movements of the body in the FB direction only. A minority of subjects demonstrated an initial postural shift in response to stimulus onset. For these subjects, it may have been the case that their postural reference frame shifted in alignment with the stimulus, if only briefly. Our data show that although some individuals change body posture at stimulus onset, most do not. In conclusion, the results of this experiment suggest that postural instability is neither a prerequisite nor a symptom of cybersickness.

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