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

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A R T I C L E I N F O

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It has been suggested that postural instability is necessary for cybersickness to occur. Seated and standing subjects used a head-mounted display to view a virtual tunnel that rotated about their line of sight. We found that the offset direction of perceived vertical settings matched the direction of the tunnel's rotation, so replicating earlier findings. Increasing rotation speed caused cybersickness to increase, but had no significant impact on perceived vertical settings. Postural sway during rotation was similar to postural sway during rest. While a minority of subjects exhibited postural sway in response to the onset of tunnel rotation, the majority did not. Furthermore, cybersickness increased with rotation speed similarly for the seated and standing 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 et al. (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 (Asch and Witkin, 1992; Kleint, 1936; Witkin and Asch, 1948). Howard and Childerson (1994) found that exposure of seated subjects to a rotating furnished tunnel produced the sensation of tumbling, and Allison et al. (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 (Apthorp and Palmisano, 2014; Flanagan et al., 2004; Reed-Jones et al., 2008; Smart et al., 2002; Stoffregen et al., 2000; Villard et al., 2008), others have found that the relationship between postural stability and VIMS is less clear (Akizuki et al., 2005; Guerraz and Bronstein, 2008; Häkkinen et al., 2002; Wang et al., 2010).

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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 (Bonato et al., 2008; Bubka et al., 2006; Classen et al., 2011; Diels and Howarth, 2011; Flanagan et al., 2004; Golding et al., 2009; Hettinger et al., 1990; Keshavarz et al., 2014b; Lee et al., 1997; Smart et al., 2002; Stoffregen and Smart, 1998), others have found only weak or no correlation between vection magnitude and VIMS severity (Golding et al., 2012; Keshavarz et al., 2014a; Lawson, 2001). For example, Fushiki et al. (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 et al. (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

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 $\times$ 1080 pixels per eye with a refresh rate of 75 Hz. The field of view was 100 $\times$ 100 degrees of visual angle. Internal tracking of head rotations and translational movements occurred at 1 KHz. 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.

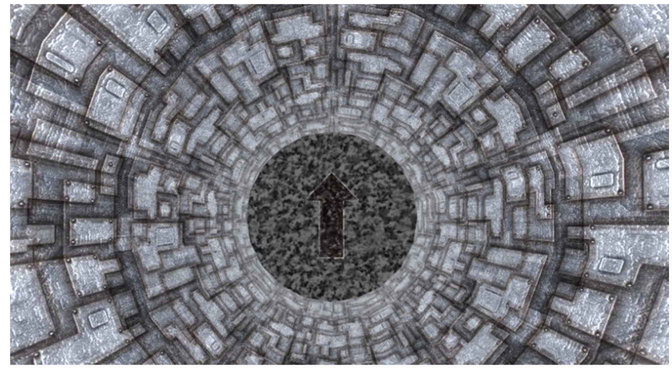

Fig. 1. Screenshot of the VE used in seated and standing conditions. The tunnel rotated about a central disk upon which an arrow appeared intermittently for use in perceived vertical settings.

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 s. 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 s. The six speeds were 6, 17, 28, 38, 49, and 60 deg/sec. After 15 s, a black arrow appeared at a random orientation on the central disk. The subject then had an additional 15 s 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 s, 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 colour of the arrow changed to blue for confirmation and to red if the subject had not yet responded and only 5 s 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