Assessing Postural Instability and Cybersickness Through Linear and Angular Displacement

Christopher Widdowson, **Israel Becerra**, **Cameron Merrill**, **Ranxiao Frances Wang**, and **Steven LaValle**, University of Illinois at Urbana–Champaign, USA

Objective: To examine the hypothesis that constant speed is more comfortable than variable speed profiles and may minimize cybersickness.

Background: Current best practices for virtual reality (VR) content creation suggest keeping any form of acceleration as short and infrequent as possible to mitigate cybersickness.

Methods: In Experiment 1, participants experienced repetitions of simulated linear motion, and in Experiment 2, they experienced repetitions of a circular motion. Three speed profiles were tested in each experiment. Each trial lasted 2 min while standing. Cybersickness was measured using the Simulator Sickness Questionnaire (SSQ) and operationally defined in terms of total severity scores. Postural stability was measured using a Wii Balance Board and operationally defined in terms of center of pressure (COP) path length. Postural measures were decomposed into anterior-posterior and medial-lateral axes and subjected to detrended fluctuation analysis.

Results: For both experiments, no significant differences were observed between the three speed profiles in terms of cybersickness or postural stability, and none of the baseline postural measures could predict SSQ scores for the speed profile conditions. An axis effect was observed in both experiments such that normalized COP movement was significantly greater along the anterior-posterior axis than the medial-lateral axis.

Conclusion: Results showed no convincing evidence to support the common belief that constant speed is more comfortable than variable speed profiles for scenarios typical of VR applications.

Application: The present findings offer guidelines for the design of locomotion techniques involving traversal in VR environments.

Keywords: simulator sickness, motion sickness, virtual environments, immersive environments, gait, posture

Address correspondence to Christopher Widdowson, Department of Psychology, University of Illinois at Urbana–Champaign, 603 East Daniel St., Champaign, IL 61820, USA; e-mail: widdwsn2@illinois.edu.

HUMAN FACTORS
Vol. XX, No. X, Month XXXX, pp. 1–16
DOI: 10.1177/0018720819881254
Article reuse guidelines: sagepub.com/journals-permissions

INTRODUCTION

Broadly speaking, virtual reality (VR) technology consists of any device that places a user in a simulated environment that can be perceived as real and interactable. Typically, this consists of a head-mounted display (HMD) that is positionally tracked and projects light onto the retinas, producing a stereoscopic image. Shortcomings in the operation or engineering of VR devices can sometimes result in user discomfort, often manifested as cybersickness.

Cybersickness is defined here as a syndrome related to HMD use that is primarily visual in nature but may consist of nonvisual or multisensory stimulation and is caused by multiple factors (Kennedy & Fowlkes, 1992). Major symptoms include, but are not limited to, headache, disorientation, fatigue, pallor, nausea, drowsiness, and incapacitation (Kennedy, Drexler, Compton, Stanney, & Harm, 2001; Kolasinski, 1995). Cybersickness is distinguished from other motion illnesses, such as simulator sickness or sea sickness, in that the symptom profile is centered on disorientation-like symptoms rather than oculomotor or nauseogenic symptoms (Rebenitsch & Owen, 2016; Stanney, Kennedy, & Drexler, 1997).

Postural stability is another phenomenon that has been found to be related to motion sickness (Bonnet, Faugloire, Riley, Bardy, & Stoffregen, 2006; Smart, Stoffregen, & Bardy, 2002; Stoffregen, Chang, Chen, & Zeng, 2017; Stoffregen, Faugloire, Yoshida, Flanagan, & Merhi, 2008) and even to cybersickness in HMD-based VR (Arcioni, Palmisano, Apthorp, & Kim, 2018). This has positioned postural stability as one of the methods for detecting and estimating the severity of cybersickness symptoms (Rebenitsch & Owen, 2016). Such a method has the advantage of providing objective, low-cost measures with continuous symptom levels. Typical postural stability measures include time until failure when maintaining a specific stance, stance breaks, average variability of movement along a given axis, speed of movement along a given axis, and so on.

Although cybersickness has been referred to as a subtype of motion sickness known as visually induced motion sickness (VIMS) (Kennedy, Lanham, Drexler, Massey, & Lilienthal, 1997; LaViola, 2000; McCauley & Sharkey, 1992) (VIMS is like traditional motion sickness with the exception that physical movement is limited or absent; however, the integrity of the vestibular system is still essential for the development of VIMS, for example, labyrinthine-defective patients are immune to VIMS [Cheung, Howard, & Money, 1991]. Because the provocative motion stimulus in modern VE systems can be visual, nonvisual, or multisensory in nature, cybersickness can include aspects from both VIMS and traditional motion sickness and beyond [Keshavarz, Riecke, Hettinger, & Campos, 2015].), it is not the same as traditional motion sickness. For example, people who report symptoms related to VR usage, as measured with the Simulator Sickness Questionnaire (SSQ), do not necessarily report being motion sick when assessed with a separate direct question on motion sickness (Chang, Chen, Kung, & Stoffregen, 2017; Li et al., 2018; Stoffregen et al., 2008). Therefore, occurrences of cybersickness may be partially due to motion sickness in some cases, but it also has its own unique causes and symptoms that do not share with traditional motion sickness.

The occurrence of cybersickness is closely related to the sensation of contradirectional self-motion known as vection, that is, the experience of self-motion when a large region of the visual field is in motion while the observer is stationary (Bos, Bles, & Groen, 2008; Nooij, Pretto, Oberfeld, Hecht, & Bülthoff, 2017; Palmisano, Allison, Schira, & Barry, 2015). Vection occurs because the optic flow pattern specifies the direction and speed of object motion resulting from the self-movement of an observer. For example, the flow pattern of the optical array may consist of a projection of the environment to a point that is centrifugal with respect to the direction of motion, resulting in an expansion or contraction of the optical flow field as a function of forward or backward motion (Gibson, 1958).

Vection can occur for both linear and circular motions. Linear vection through the anterior-posterior (AP) axis is commonly experienced during VE traversal, especially in driving or flight simulators; however, circular vection through the yaw, pitch, and roll axes is also possible. For linear vection (head stable), the threshold of detection occurs at the perceptual limits of image motion detection by the visual system (>0.001 m/s) and saturates at approximately 1 m/s (Berthoz, Pavard, & Young, 1975). Other reports of vection saturation involving unconstrained head motion indicate a value as high as 10 m/s (So, Lo, & Ho, 2001). For circular vection, saturation has been observed for optokinetic stimuli rotating at 60°/s with 24 moving contrasts (15° per visual angle).

A common assumption about the cause of cybersickness is sensory conflict in the VR simulation. During real locomotion, afferent signals from the visual, vestibular, and/or somatosensory systems are transmitted to the central nervous system and are concordant. These signals are not concordant for motion perception in nonambulatory VE systems; however, expansion or contraction of the optical array, as detected by the visual system, will typically predominate over signals of stationarity detected by the vestibular and/or somatosensory systems. The resulting visual–vestibular conflict is supposed to be one of the main causes of cybersickness (Keshavarz, Hecht, & Lawson, 2014; Reason & Brand, 1975).

Partially based on this hypothesis, there is a widely held belief that traversal through a VE according to constant velocity is more comfortable than moving with varying velocity (Jerald, 2015; LaValle, 2016). Variations in a velocity vector can be produced by either changing its direction or changing its magnitude (speed), which would yield a sensory conflict for a VE user at rest. To illustrate this phenomenon, consider the following scenario. Assume linear motion in the VE aligned with a reference axis, such that its direction remains constant but allows the travel speed to be varied—such linear motion in the VE would produce the respective optical flow to simulate the self-motion experience. Then, consider that you apply the linear motion according to one of the two speed profiles (time-parameterized functions): a constant speed profile and a time-varying speed profile (see Figure 2). A constant speed profile would yield a sensory conflict between the visual and vestibular systems at the beginning and end of the motion. On the contrary, a time-varying speed profile might lead to a smaller conflict but is distributed throughout the duration of the movement.

The assumption is that the constant speed profile would induce less sickness than the time-varying profile, that is, it is preferable to have large sensory conflict for a very short time interval, as opposed to a smaller, sustained conflict over a longer time interval. To the best of our knowledge, the work from Dorado and Figueroa (2014) comes closest to formally addressing such a scenario; however, their focus was to identify ways to minimize perceived cybersickness after moving up-and-down stairs. Despite testing different speed profiles, they did not find conclusive results regarding the effects of cybersickness as a function of different speed profiles.

In this work, our main goal is to confirm or reject the hypothesis that a larger sensorial mismatch over a brief period is preferable to a smaller mismatch over a longer period, in terms of self-reported cybersickness. In addition, postural stability has been shown to predict motion sickness (Stoffregen, Chen, Varlet, Alcantara, & Bardy, 2013), and potentially cybersickness as well (Arcioni et al., 2018); therefore, postural stability (as measured by center of pressure [COP] path length and COP detrended fluctuation analysis [DFA] alpha values) has also been included for the purpose of analyzing a physiological signal that might offer an objective and potentially more sensitive indicator of cybersickness. Three speed profiles are evaluated as a function of linear and angular displacement in two separate experiments. Results can help validate guidelines for the development of VR content, especially as it pertains to navigation and traversal in virtual worlds.

EXPERIMENT 1: LINEAR DISPLACEMENT

Materials and Methods

Participants. The experiment was conducted in the Virtual Reality and Spatial Cognition Lab in the Department of Psychology at the University of Illinois at Urbana–Champaign. A total of 24 participants completed the experiment. All participants were screened for color blindness using pseudoisochromatic color plates and had normal or corrected-to-normal visual acuity. This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at the University of Illinois at Urbana–Champaign. Informed consent was obtained from each participant.

Virtual environment (VE). The HTC Vive VR headset (HTC, Taiwan, China, and Valve, Bellevue, WA, USA) was used to display experimental stimuli. The HMD consists of two low-persistence AMOLED displays (90 Hz) with a combined resolution of 2,160 × 1,200 pixels (1,080 × 1,200 per eye) and approximately 110° horizontal field of view. The system achieves six degrees of freedom head tracking by fusing sensor data from an onboard inertial measurement unit and a pair of spinning infrared laser emitters, positioned diagonally and in opposite corners of a $3 \times 3 \times 3$ m^3 tracking volume. An array of embedded photodiodes detects the infrared laser light.

The VE consisted of a $17.68 \times 1.83 \times 2.31$ m^3 hallway rendered in the Unity game engine (2017.1.0f2) and presented on a Windows 10 computer (3.3 GHz i7-5820K CPU; 32 GB RAM; NVIDIA GeForce GTX 980 Ti graphics). Each speed profile described the path of a virtual camera fixed to a 9.8-m linear trajectory. The user's camera height is automatically instanced into the VE based on the position of the HMD in the physically tracked volume; there is no discrepancy between perceived and actual height in the VE (see Figure 1).

Different rates of acceleration induced by the speed profiles in the VE will cause different sensorial mismatches between the visual and vestibular systems. In this study, we compared the effects of three speed profiles, namely, constant, ramp, and polynomial, whose parameters were chosen as follows. The duration of the traversal lasted 7 s, which is greater than the reported onset times for linear vection (around 1 s according to Berthoz et al., 1975). Then, a walking speed of 1.4 m/s was set for the constant speed profile; the total distance traveled was thus constrained to 9.8 m. The three speed profiles were designed to have the same duration and travel

Figure 1. Participant standing on the Wii Balance Board in static, forward-facing pose (left). Perspective view of the VE in Experiment 1 (right). VE = virtual environment.

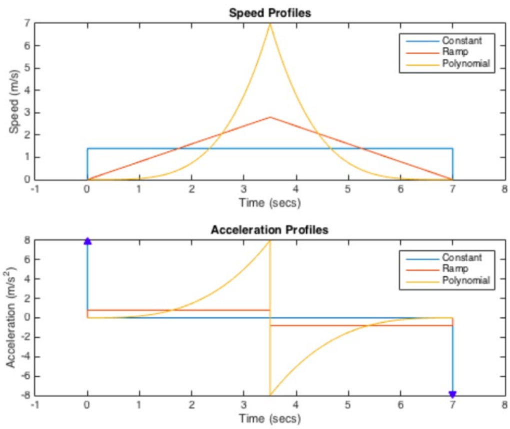

Figure 2. Three speed profiles used in Experiment 1: constant, $s(t) = a$; ramp, $s(t) = b \times t$; and polynomial, $s(t) = c \times t^4$. The acceleration and deceleration stages of each speed profile are symmetric.

distance, that is, 7-s duration and 9.8-m distance, which uniquely defines the parameters of the two remaining speed profiles: ramp and polynomial. Peak speed and acceleration for each profile are as follows: constant (1.4 m/s, ∞ m/s^2) (While stopped and during the actual motion with constant speed, the acceleration is zero. In the transition from the stopped state to the moving state, the change of speed is almost instantaneous, which corresponds to a very large value of acceleration that we represent with infinity.), ramp (2.8 m/s, 0.8 m/s^2), and polynomial (7.0 m/s, 8.0 m/s^2); acceleration and deceleration stages of the speed profiles are symmetric (see Figure 2). Speed profiles are defined by the following equations: constant, $s(t) = a$; ramp, $s(t) = b \times t$; and polynomial, $s(t) = c \times t^4$.

For the constant speed profile, there are large peaks in acceleration, but only at the beginning and end of the trajectory. For the ramp speed profile, the acceleration magnitude remains constant throughout the duration of the trajectory. For the polynomial speed profile, the respective acceleration profile is a third-degree polynomial curve. Thus, the constant speed profile induces the largest magnitude acceleration, but it is experienced only during a brief period, whereas the ramp speed profile induces a smaller magnitude acceleration, but across the entire trajectory. The polynomial profile exhibits periods in which the acceleration magnitude is smaller than what is observed in the ramp speed profile, but other periods in which the acceleration magnitude is larger. For both the ramp and polynomial speed profiles, there is a reversal in acceleration at the midpoint of the trajectory.

The SSQ. Cybersickness is often measured with the SSQ (Jerald, 2015; Kennedy, Lane, Berbaum, & Lilienthal, 1993). The SSQ was developed to measure motion sickness–like symptoms related to the operation of military flight and driving simulators, and so it was originally referred to as a measure of "simulator sickness." The SSQ was later co-opted to measure motion sickness–like symptoms in head-mounted and other VR systems, which produced a symptom profile that centered on disorientation, that is, cybersickness. The present study used the SSQ to assess levels of pre- and post-exposure symptoms throughout the experiment. The SSQ is a 16-item inventory with responses given on a 4-point Likert-type scale. Factor analysis reveals three components: oculomotor discomfort, disorientation, and nausea (Kennedy et al., 1993). The SSQ generates a total severity score and a score for each component. Scale scores for each item are computed by multiplying the reported value for each item by a weight and then summing across items for that component; weighted scale scores for each component can be found by multiplying each component by a unique weight. A total severity score is computed by summing scale scores across the three components and multiplying by a weight. The maximum total severity score for the SSQ is approximately 300, with scores >20 indicating a problematic simulator (Kennedy et al., 2001).

Postural measures. Laboratory-based assessment of human balance performance typically focuses on measures of postural stability to characterize dynamic changes in postural control. For the present study, postural stability refers to the time course of center of mass (COM) oscillations in the AP and medial-lateral (ML) planes and is closely related to the displacement of the COP during quiet standing (Morasso, Spada, & Capra, 1999). The COP trajectory is defined by the change in position of the point of application of the ground reaction force vector over time—often measured using a force platform—with larger values of COP total path length thought to indicate lesser postural stability (Winter, 1995).

Force platforms are considered the gold standard for the objective assessment of standing balance, but can be expensive, difficult to calibrate, and inconvenient to transport. Subjective measures of balance that do not require specialized equipment are also available (e.g., Berg Balance Scale or Tinetti Performance-Oriented Mobility Assessment) but may offer limited precision and can suffer from ceiling effects, emphasizing the need for low-cost, laboratory-grade alternatives in the assessment of standing balance (Berg, Maki, Williams, Holliday, & Wood-Dauphinee, 1992; Gustavsen, Aamodt, & Mengshoel, 2006; Tinetti, 1986).

Recent work has demonstrated the utility of the Nintendo Wii Balance Board (WBB; Nintendo, Kyoto, Japan) as an alternative to force platform systems (Clark et al., 2010). The WBB is like a scientific-grade force platform in that it contains four load cells that gauge force distribution and the time course of the COP trajectory. Bartlett, Ting, and Bingham (2014) recommend that the WBB should not be considered equivalent to laboratory-grade equipment, but might be sufficient to record low-frequency movements such as quiet standing. In a reliability and validity analysis by Park and Lee (2014), the WBB showed high concurrent validity with a laboratory-grade force platform, as well as high inter- and intra-rater reliability, as assessed by intraclass correlation coefficient values between .80 and 1.00. The present study used a WBB in combination with a custom Python backend to record balance measurements over a Bluetooth connection (40 Hz, which has shown to be sufficiently sensitive in a similar context by Scoppa, Capra, Gallamini, & Shiffer, 2013) for subsequent analysis; source code has been made available in a public repository: https://github.com/CamMerrill/WiiSway.

Procedure. The experiment began with the pre-exposure SSQ to establish a baseline measure of cybersickness before entering VR. We then recorded baseline postural stability while standing still in the VE for 2 min (no simulated movement); while in VR, participants were asked to keep their eyes open, hands by their sides, and affix their gaze forward. Participants were then given a 2-min break outside of VR. Next, participants were presented with one of the three speed profiles in VR for 2 min—12 repetitions of a 7-s trajectory (9.8 m), beginning and ending with a 1.5-s pause; the screen faded to black and reset the participant's position at

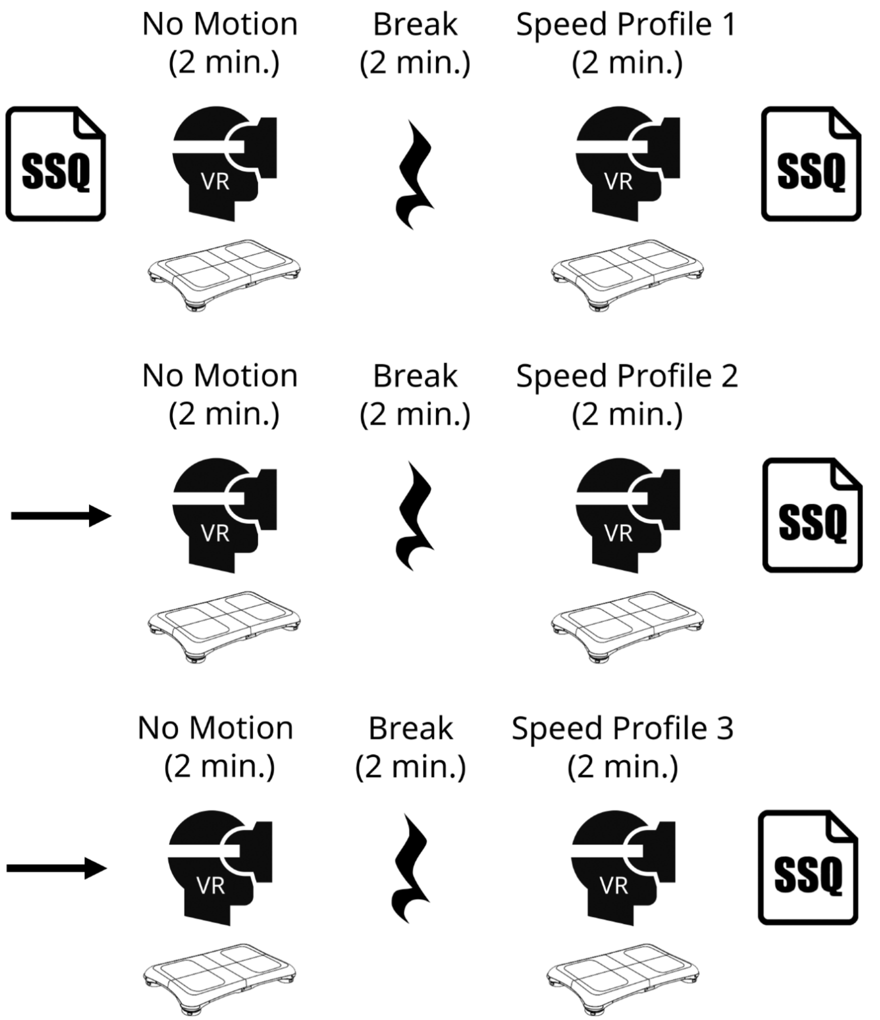

Figure 3. Diagram of the experimental procedure (read left to right, top to bottom). The No Motion stage was the baseline measurement of postural stability for the following speed profile. SSQ = Simulator Sickness Questionnaire; VR = virtual reality.

the terminal point. Afterward, participants completed the post-exposure SSQ. This process was repeated (see Figure 3) until all speed profiles were tested; each speed profile was experienced in counterbalanced order across participants, resulting in four assessments of cybersickness and six recordings of postural stability. The entire experiment lasted approximately 30 min.

Data analysis. In this study, postural stability is operationalized in terms of COP path length and is computed as follows. Consider that a trial starts at time "0" and ends at a time indexed by "*T*." Also consider that at time "*t*" the COP is located at coordinates (x_t, y_t). The path length traveled per trial by the COP (in millimeters) is computed using the following equation:

$$\sum_{t=0}^{T-1} \sqrt{\left(x_{t+1} - x_t\right)^2 + \left(y_{t+1} - y_t\right)^2}.$$

The temporal dynamics of postural stability were evaluated by conducting a DFA on the COP time series for AP and ML axes independently; it is recommended to apply DFA to the two principal motion axes separately because AP and ML motions are characterized by distinct muscle/joint action control (Kent et al., 2012). DFA was implemented using the PhysioToolkit-PhysioNet software library (MATLAB) developed by Goldberger et al. (2000). (PhysioToolkit DFA module requires some parameters to be specified: detrend using a polynomial of degree *p* [default: $p = 1$; linear]; minBoxSize – smallest box width [default: $2p + 2$]; maxBoxSize – largest box width [default: $N/4$, with *N* being the total number of points in the signal]. Default values were chosen for both Experiments 1 and 2.) In brief, DFA is a modified root mean square (RMS) analysis of a random walk that computes the RMS error of linear fits over progressively larger bins. DFA is a frequently used method to detect the presence of long-range correlations and fractal dynamics in a physiological time series. A detailed description of the algorithm can be found in Peng, Havlin, Stanley, and Goldberger (1995), but a summary has been adapted from the text and provided later.

First, a time series of *N* samples is integrated and divided into equal-sized boxes of length *n*; box size, therefore, represents the scale of the observed signal for that moment in time. Next, a least-squares line is fit to each box of length *n*; let $y_n(k)$ denote the *y* coordinate of the straight-line segments. The integrated time series, $y(k)$, is then detrended by subtracting the local trend $y_n(k)$ from each box. The RMS fluctuation is given by

$$F(n) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left[y(k) - y_n(k)\right]^2}.$$

The calculation is then repeated for all box sizes to determine the relationship between the average fluctuation as a function of box size, $F(n)$, and the box size, *n*. The growth in fluctuation magnitude is equal to the slope of the function in log-log space, called an alpha value; if $\alpha > .5$, then the time series is autocorrelated at some time scale; if $\alpha < .5$, then the time series is anticorrelated at some time scale; if $\alpha = .5$, then the signal is uncorrelated, for example, white noise; $\alpha = 1$ indicates maximal self-similarity in a signal, for example, pink noise; $\alpha > 1$ indicates decreased complexity, for example, Brownian noise, $\alpha = 1.5$.

To examine the effect of speed profile on postural stability and cybersickness, COP movement data were decomposed into AP and ML axes and normalized by subtracting the baseline COP path length preceding each condition from the COP path length observed during simulation. COP movement was examined in a 2 (AP, ML) × 3 (Constant, Ramp, Polynomial) repeated-measures ANOVA. The time series was also subjected to a DFA to evaluate temporal characteristics of the COP trajectories. DFA was applied to AP and ML axes independently, resulting in alpha values for both axes. DFA alpha values were normalized according to the same procedure described earlier and included in a 2 (AP, ML) × 3 (Constant, Ramp, Polynomial) repeated-measures ANOVA.

Cybersickness was operationalized in terms of self-reported total severity score, as measured by the SSQ. Total severity was computed by summing the weighted subscales of the SSQ (see section "The SSQ"). Cybersickness ratings were analyzed in a Friedman test with four levels, including a baseline measurement and three speed profiles: constant, ramp, and polynomial. In this and subsequent analyses, Greenhouse–Geisser epsilon-adjusted degrees of freedom are reported when Mauchly's test of sphericity has a probability less than .10.

Results

Cybersickness. Scores on the SSQ are not normally distributed and so were analyzed using nonparametric statistics (Kennedy et al., 1993). A Friedman test was conducted to determine whether there was a statistically significant difference in total severity scores for the three speed profiles and a baseline measurement. The data contained one outlier, as assessed by examination of studentized residuals for values greater than ±3 (Kirk, 2013). Total severity was not normally distributed at any level of the within-subject factor, as assessed by Shapiro–Wilk's test ($p < .05$). There was a statistically significant difference in total severity between the three speed profiles and a baseline period, $\chi^2(2) = 17.953$, $p < .001$. Post hoc analysis with Bonferroni adjustment revealed a statistically significant increase in total severity from baseline ($Mdn = 5.61$) for the polynomial ($Mdn = 22.44$; $p = .001$, $d = 0.669$) speed profile, but not the

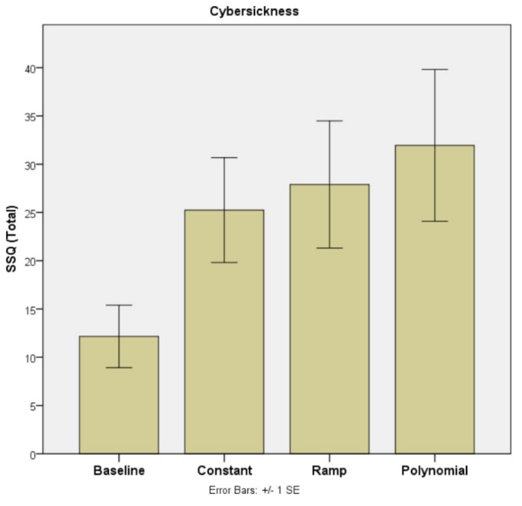

Figure 4. Results of SSQ total scores in the four conditions in Experiment 1. The error bars show ±1 standard error from the mean SSQ total scores of the 24 participants. SSQ = Simulator Sickness Questionnaire.

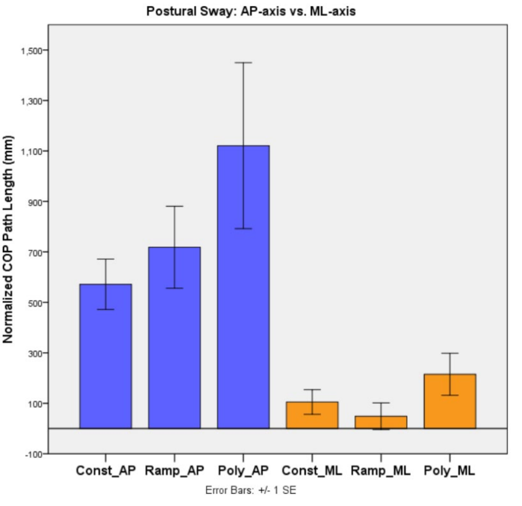

Figure 5. Results of COP movement through the AP and ML axes for all speed profiles in Experiment 1. The error bars show ±1 standard error from the mean normalized COP path length of the 24 participants. COP = center of pressure; AP = anterior-posterior; ML = medial-lateral.

constant (*Mdn* = 16.83; p = .071) or ramp (*Mdn* = 14.96; p = .131) speed profile. No significant differences were observed between the constant and ramp (p = 1.00), constant and polynomial (p = 1.00), or ramp and polynomial (p = .974) speed profiles. Figure 4 shows the mean SSQ total scores for each condition.

Postural stability. A two-way repeated-measures ANOVA was conducted to determine whether there was a statistically significant difference in normalized COP path length through the AP and ML axes for three speed profiles: constant, ramp, and polynomial. The data contained three outliers, as assessed by examination of studentized residuals for values greater than ±3 (Kirk, 2013). Normalized COP path length was normally distributed for all three speed profiles in the ML ($p > .05$), but not AP axis ($p < .05$), as assessed by Shapiro–Wilk's test of normality of the studentized residuals. There was a statistically significant difference in normalized COP path length between the AP and ML axes, $F(1, 23) = 21.33, p < .001, \eta_p^2 = .48$, with greater COP movement through the AP (M = 803.64, 95% confidence interval [CI] = [451.96, 1,155.32]) compared with the ML axis (M = 122.97, 95% CI = [38.20, 207.75]) (see Figure 5). Neither the interaction term nor the main effect of speed profile elicited a statistically significant difference in normalized COP path length, $F(1.52, 35.07) = 2.81$, $p = .087$; $F(1.41, 32.33) = 2.47$, $p = .116$, respectively.

A two-way repeated-measures ANOVA was conducted to determine whether there was a statistically significant difference in normalized DFA alpha values through the AP and ML axes for three speed profiles. The data contained no outliers, as assessed by examination of studentized residuals for values greater than ±3 (Kirk, 2013). Normalized DFA alpha values were not normally distributed for the constant speed profile through the AP axis ($p < .05$), as assessed by Shapiro-Wilk's test of normality of the studentized residuals. Neither the main effect of speed profile or body axis nor the interaction term elicited a statistically significant difference in normalized DFA alpha values, $F(2, 46) = 1.289$, $p = .285$; $F(1, 23) = 1.028$, $p = .321$; $F(2, 46) = 2.130$, $p = .130$, respectively.

An exploratory multiple regression analysis was conducted to test whether individual differences in baseline postural stability could predict post-exposure cybersickness ratings. Post-exposure total severity scores were averaged across the three speed profiles and included in the model as a single outcome variable. COP path length and DFA alpha values were each averaged across the three baseline conditions, per AP and ML axes, resulting in four predictor variables that entered the model simultaneously. Evidence for a first-order autocorrelation of the residuals was not detected, as assessed by a Durbin–Watson statistic of 1.496. Visual inspection of partial regression plots and a plot of studentized residuals against the unstandardized predicted values revealed a somewhat linear relationship. The assumption of homoscedasticity was met, as assessed by the Koenker test of heteroscedasticity, $p = .805$. The assumption of multicollinearity was met, as assessed by tolerance values greater than 0.10. There was one outlier, as assessed by studentized deleted residual greater than ±3 standard deviations, and values for Cook's distance were below 1. Visual inspection of the normal Q-Q plot of studentized residuals revealed an approximately normal distribution. The multiple regression model did not achieve statistical significance, $F(4, 23) = .190$, $p = .941$, adj. $R^2 = -.164$. None of the four predictor variables achieved statistical significance, $p > .05$.

Discussion

In Experiment 1, participants experienced linear visual motion through three speed profiles, each experienced for 2 min at a time. Postural stability and cybersickness were assessed for each condition and compared against a corresponding baseline period. Results showed that there was a significant difference in speed profile conditions in terms of self-reported cybersickness. Importantly, this effect was driven by a baseline period, and there was no significant difference in cybersickness ratings between the three speed profiles. That is, the SSQ scores did not differ depending on whether participants experienced visual motion during a constant, ramp, or polynomial speed profile.

Moreover, further analysis on COP through the AP and ML axes showed significantly greater COP movement through the AP compared with the ML axis. This conclusion stands to reason that participants experienced strong visual cues indicating forward self-motion, that is, expanding optical flow, but no side motion, which may have led to more COP movement along the AP axis. However, the postural analysis did not show a significant difference among the three speed profiles, in the measure of both COP and DFA. Therefore, in this experiment, we failed to find any experimental evidence to support the common belief that constant speed profile is more comfortable for the observer and should lead to less cybersickness.

One possible reason that our cybersickness measures did not differ in terms of the experienced speed profile is that the intensity (or quality) of the speed profiles assessed was not sufficient to differentiate postural stability or cybersickness as it was assessed. However, note that the total severity scores indicated a significant departure from baseline, the magnitude of which is indicated by Kennedy et al. (2001) as a "problem simulator," suggesting that the VR simulation did induce cybersickness, even though the degree of cybersickness did not differ among the speed profile conditions. Moreover, the velocity and acceleration profiles experienced were selected to be generalizable to a variety of casual and intense movements that might be experienced in consumer VR applications. For example, the most casual motion profile occurs in the constant speed profile at 1.4 m/s, which mimics the average human walking speed. On the contrary, the polynomial condition exhibits peak velocity at 7.0 m/s (15 mph). Therefore, although it remains possible that stronger speed profile manipulations may allow one to demonstrate some difference in cybersickness, our results suggest that under common VR application scenarios, the effect of speed profile may be negligible for linear motion.

EXPERIMENT 2: ANGULAR DISPLACEMENT

Materials and Methods

Methods for Experiment 2 were identical to those of Experiment 1 with the following exceptions described below.

Participants. A group of 24 participants (different from Experiment 1) completed the experiment. All participants were screened for color blindness using pseudoisochromatic color plates and had normal or corrected-to-normal visual acuity. This research complied with the

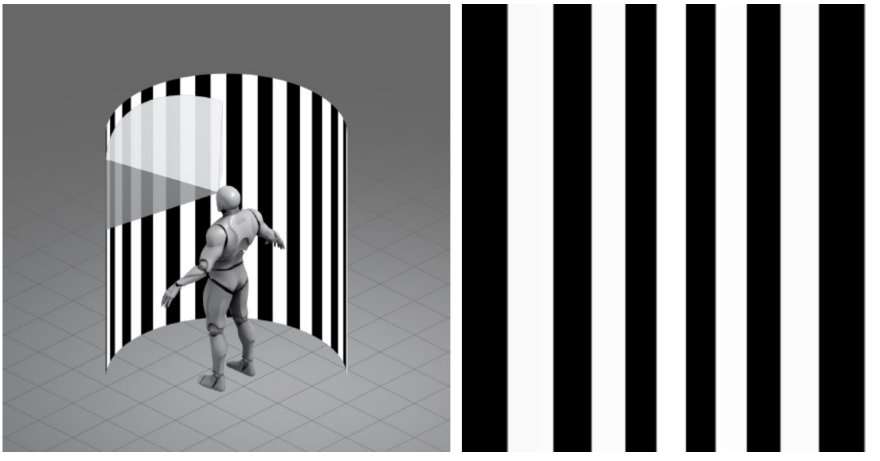

Figure 6. Schematic illustration of user position, field of view, and optokinetic stimulus used in Experiment 2 (left). First-person perspective of the optokinetic stimulus used in Experiment 2 (right).

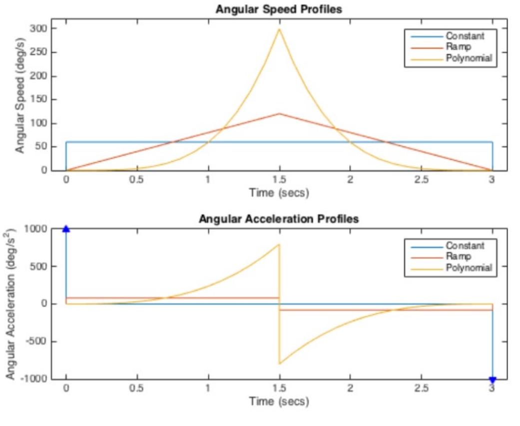

Figure 7. The speed profiles used in Experiment 2 were identical to those of Experiment 1 but converted to rates of angular displacement.

American Psychological Association Code of Ethics and was approved by the Institutional Review Board at the University of Illinois at Urbana–Champaign. Informed consent was obtained from each participant.

VE. The VE consisted of an open cylinder with the user's perspective centered at the origin of the cylinder. The inner faces of the cylinder were textured with a black and white striped pattern that subtended a visual angle of 30° per cycle, to emulate an optokinetic drum (see Figure 6). This pattern was selected based on the 15° per cycle spatial frequency reported in Hu et al., 1997, with which self-reported nausea manifested maximally. The following parameters for the rotational motion speed profiles were selected. The rotation angle was set to 180°, which corresponds to the greatest change in the AP axis direction that one might experience while navigating in a VE. The constant speed profile was selected to have a speed of 60°/s, a rotational speed at which sickness in optokinetic drums has been found to peak (Hu, Stern, Vasey, & Koch, 1989). This sets the duration of the movement to 3 s. The other two speed profiles were selected to travel the same 180° in 3 s. Peak velocity and acceleration for each profile are as follows: constant (60°/s, ∞), ramp (120°/s, 80°/s^2), and polynomial (300°/s, 800°/s^2); acceleration and deceleration stages of the speed profiles were symmetric (see Figure 7).

Procedure. The procedure in Experiment 2 was identical to that of Experiment 1 except that participants rotated 180° through a point for 3 s, beginning and ending with a 1.5-s pause; the screen faded to black and reset the participant's orientation at the termination point. Initial rotation direction (left or right) was randomized across all trials.

Results

Analysis for Experiment 2 was identical to that of Experiment 1 unless otherwise specified.

Cybersickness. A Friedman test was conducted to determine whether there was a statistically significant difference in total severity

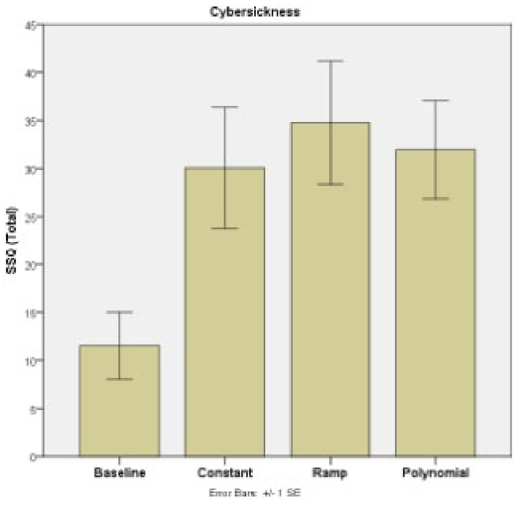

Figure 8. Results of SSQ total scores in the four conditions in Experiment 2. The error bars show ±1 standard error from the mean SSQ total scores of the 24 participants. SSQ = Simulator Sickness Questionnaire.

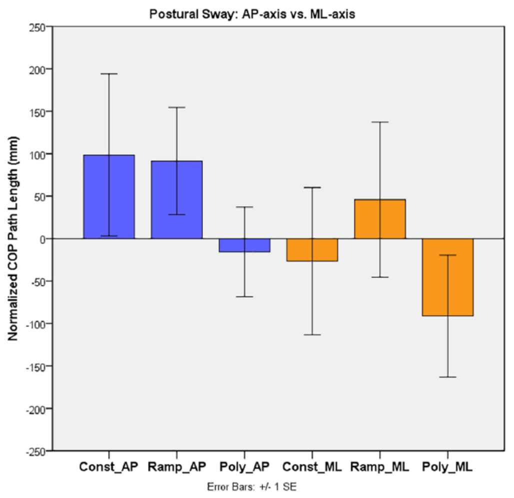

Figure 9. Results of COP movement through the AP and ML axes for all speed profiles in Experiment 2. The error bars show ±1 standard error from the mean normalized COP path length of the 24 participants. COP = center of pressure; AP = anterior-posterior; ML = medial-lateral.

scores for the three speed profiles and a baseline measurement. The data contained one outlier, as assessed by examination of studentized residuals for values greater than ±3 (Kirk, 2013). Total severity was not normally distributed at any level of the within-subject factor, as assessed by Shapiro-Wilk's test ($p < .05$). There was a statistically significant difference in total severity between the three speed profiles and a baseline period, $\chi^2(2) = 26.304$, $p < .001$. Post hoc analysis with Bonferroni adjustment revealed statistically significant increases in total severity from baseline (*Mdn* = 3.74) for the polynomial (*Mdn* = 29.92; $p = .001$, $d = 0.962$), constant (*Mdn* = 16.83; $p = .006$, $d = 0.692$), and ramp (*Mdn* = 26.18; $p < .001$, $d = 0.813$) speed profiles. No significant differences were observed between the constant and ramp ($p = 1.00$), constant and polynomial ($p = 1.00$), or ramp and polynomial ($p = 1.00$) speed profiles. Figure 8 shows the mean SSQ total scores for each condition.

Postural stability. A two-way repeated-measures ANOVA was conducted to determine whether there was a statistically significant difference in normalized COP path length through the AP and ML axes for three speed profiles. The data contained one outlier, as assessed by examination of studentized residuals for values greater than ±3 (Kirk, 2013). Normalized COP path length was not normally distributed for the polynomial speed profile through the ML axis ($p < .05$), as assessed by Shapiro–Wilk's test of normality of the studentized residuals. There was a statistically significant difference in normalized COP path length between the AP and ML axes, $F(1, 23) = 6.53$, $p = .018$, $\eta_p^2 = .221$, with greater COP movement through the AP axis ($M = 58.05$, 95% CI = [−31.91, 148.01]) compared with the ML axis ($M = -23.96$, 95% CI = [−129.80, 81.87]) (see Figure 9). Neither the interaction term nor the main effect of speed profile elicited a statistically significant difference in normalized COP path length, $F(2, 46) = 0.76$, $p = .472$; $F(2, 46) = 0.676$, $p = .514$, respectively.

A two-way repeated-measures ANOVA was conducted to determine whether there was a statistically significant difference in normalized DFA alpha values through the AP and ML axes for three speed profiles. The data contained no outliers, as assessed by examination of studentized residuals for values greater than ±3 (Kirk, 2013). Normalized DFA alpha values were not normally distributed for the constant speed profile through the AP axis ($p < .05$), as assessed by

Shapiro-Wilk's test of normality of the studentized residuals. The main effect of speed profile showed a statistically significant difference in normalized DFA values between the constant (M = 0.058, 95% CI = [−0.017, 0.132]), ramp (M = −0.076, 95% CI = [−0.147, −0.006]), and polynomial (M = 0.015, 95% CI = [−0.071, 0.101]) speed profiles, $F(2, 46) = 3.392$, p = .042, $\eta_p^2 = .129$. Planned contrasts (nonorthogonal) revealed a significant difference between the constant and ramp speed profiles, $F(1, 23) =$ 6.730, p = .016, $\eta_p^2 = .226$, in terms of normalized DFA values, but not between the constant and polynomial speed profiles, $F(1, 23) = 0.555$, p = .464, or ramp and polynomial speed profiles, $F(1, 23) = 3.553$, p = .072. Neither the main effect of body axis nor the interaction term elicited a statistically significant difference in normalized DFA alpha values; $F(1, 23) = 0.824$, p = .373; $F(2, 46) = 0.372$, p = .692, respectively.

An exploratory multiple regression analysis was conducted to test whether individual differences in baseline postural stability could predict post-exposure cybersickness ratings. Post-exposure total severity scores and measures of postural stability were calculated and entered into the model identical to Experiment 1 (see section "Postural stability"). Evidence for a first-order autocorrelation of the residuals was not detected, as assessed by a Durbin–Watson statistic of 1.520. Visual inspection of partial regression plots and a plot of studentized residuals against the unstandardized predicted values revealed an approximately linear relationship. The assumption of homoscedasticity was met, as assessed by the Koenker test of heteroscedasticity, p = .368. The assumption of multicollinearity was met, as assessed by tolerance values greater than 0.10. There were no studentized deleted residuals greater than ±3 standard deviations, and values for Cook's distance were below 1. Visual inspection of the normal Q-Q plot of studentized residuals revealed an approximately normal distribution. The multiple regression model did not achieve statistical significance, $F(4, 23) = 0.436$, p = .781, adj. $R^2 = -.109$. None of the four predictor variables achieved statistical significance, $p > .05$.

Discussion

Experiment 2 examined the effect of circular visual motion through angular displacement on cybersickness and postural stability. Results from Experiment 2 mirrored those of Experiment 1, with the exception that DFA was significantly different between constant and ramp conditions. As in Experiment 1, less COP path length was observed through the ML axis compared with the AP axis, suggesting that the difference in postural way between the two axes was not specific to the linear motion, but occurs for circular motion as well. This finding casts doubt on our original hypothesis that more COP movement along the AP axis was due to the simulated forward motion. Nonetheless, in Experiment 1, the magnitude of the normalized COP path length in the AP axis was more than 5 times that which was observed in Experiment 2.

More importantly, the results again showed no evidence that speed profiles affected cybersickness, both in the direct measure of SSQ and in the indirect assessments of postural stability. Although the DFA measure showed significant difference between the constant and the ramp condition, the difference between the constant and the polynomial condition was not significant, which is inconsistent with the hypothesis that constant speed is more comfortable than the variable condition. Therefore, overall, speed profiles showed no consistent effects on cybersickness for circular motion as for linear motion.

As in Experiment 1, one potential concern is that the motion profile manipulations used here may not be strong enough to elicit observable effects on cybersickness. However, as observed in Experiment 1, post-exposure cybersickness ratings were increased from baseline, and within the range of what constitutes a problem simulator (Kennedy et al., 2001), suggesting that the VR simulations were strong enough and effective in causing cybersickness. Moreover, in keeping with Experiment 1, the quality and intensity of angular displacement were selected to represent a case in which cybersickness should be maximally observed in terms of rotational speed (Yang & Sheedy, 2011), vection saturation (Berthoz et al., 1975; So et al., 2001), and spatial frequency (Hu et al., 1997; So, Ho, &

Lo, 2001). Therefore, our findings suggest that at least in typical scenarios that were thought to be problematic for VR simulations, speed profiles have no significant effects on cybersickness for circular motion.

GENERAL DISCUSSION

The main goal of this research was to examine the hypothesis that constant speed is more comfortable than variable speed and may minimize cybersickness. As discussed in the introduction, current best practices for VR content creation suggest keeping any form of acceleration as short and infrequent as possible to mitigate cybersickness. It has also been suggested that it is preferable to have considerable mismatch for a very short time interval, as opposed to a smaller, sustained mismatch over a longer time interval. Such hypotheses led to the development of this study in which we compared three speed profiles—and their respective accelerations—to gain insight into the best locomotion methods for VR traversal. According to these common beliefs, the speed profile that should be most comfortable is the constant speed profile because it only presents instantaneous acceleration components at the beginning and end of the trajectory. Indeed, there is no other speed profile with a shorter duration and more infrequent nonzero acceleration periods.

To test this hypothesis, we examined the effects of three speed profiles (constant, ramp, and polynomial) on cybersickness in both linear and circular motions. We used both the direct measure of cybersickness (SSQ) and a potentially more sensitive, indirect assessment of the motion effect (postural stability). Regarding the SSQ measure of cybersickness, both experiments showed there was no significant difference in severity of self-reported cybersickness between speed profiles. Moreover, there was also no convincing evidence of the speed profile effect in the postural stability measurements, in both COP and DFA and for both the linear and circular motions. Taken together, our studies suggest that speed profile has negligible effect on people's cybersickness.

Our findings appear to be inconsistent with some previous research showing the effects of speed profile on cybersickness. For example, Dorado and Figueroa (2014) observed in some experiments that a constant speed profile was more comfortable than a ramp-like speed profile. However, their comparison was uneven in terms of trial duration between the two profiles; usually the ramp speed profile traveled the desired path in less time than the constant speed profile. To address such issues, this study used speed profiles that traversed the same distance (linear distance in Experiment 1 or angular distance in Experiment 2) and had the same duration.

Nevertheless, a small, nonsignificant trend was observed in both the cybersickness ratings and the COP measures, with the constant speed profile yielding the lowest total severity score. Moreover, the DFA for the circular motion was significantly lower in the constant condition than in the ramp condition, although not significantly different from the polynomial condition. These observations are consistent with the idea that constant speed is most comfortable, as the other speed profiles evoke sensorial mismatches (nonzero acceleration) for longer periods of time. Therefore, we speculate that with more extreme manipulations of the speed profile, some effects on cybersickness might be detectable. However, note that our manipulations did evoke substantial cybersickness in both experiments, as suggested by the increase in SSQ compared with baseline, and the parameters of the speed profiles were based on common VR scenarios; therefore, our findings should be representative and applicable to typical VR practices. Overall, our results provided no convincing evidence that traversing a VE with constant speed is more comfortable than traversing a VE with the other two tested speed profiles. Hence, constant speed traversal is a good option for movement in VR, but not demonstrably better than the other speed profiles for the range of visual motion tested. We believe such results to be valuable for the design of locomotion techniques to traverse VR environments.

Nevertheless, there are some limitations to this study, such as the lack of an explicit measurement of vection and the accuracy of the WBB compared with a scientific-grade force platform. However, both experiments were designed to alleviate such limitations. That is, our study primarily required the recording of low-frequency movements, for which the WBB has been shown to be adequate. Moreover, although vection was not explicitly measured, the effects of the stimuli on participants' COP movement provided some indirect indication that they were effective in inducing vection. It is also important to mention that in this study we only considered pure translational and pure rotational motions, and an analysis of multiaxial visual motion is left for future research.

Another potential limitation concerns whether aspects of the experimental procedure induced participants to modify or otherwise alter their behavior based on presumptions regarding the true intentions of the experiment (Young, Adelstein, & Ellis, 2006). In other words, it is possible that the increase in cybersickness ratings was not related to actual sensations of cybersickness, but a consequence of applying several questionnaires to the same individual. Nevertheless, comparing our results with those of Young et al. (2006) suggests that this type of demand characteristics is unlikely the sole cause of the increase in SSQ. On one hand, in that study, the demand character produced an increment in the post-exposure SSQ total scores of around 4 points (mean SSQ score of 6 in "post-test-only" condition, compared to a mean value of 10 for the "pre-/post-test" condition). In contrast, in Experiment 1, we obtained pre-exposure SSQ scores of around 11 and post-exposure SSQ scores between 25 and 32 (see Figure 4)—an increase of 14 points (up to 21 points) between the pre- and post-exposure SSQ scores, which is much larger than the 4 points attributed to demand character in Young et al. (2006).

Furthermore, according to Kennedy et al. (2001), in our work the effect of VE immersion increased the pre-exposure SSQ scores category "a simulator with significant symptoms" to a "problematic simulator"—an escalation of two categories (SSQ score of 10–15 indicates "significant symptoms"; 15–20, "symptoms are a concern"; >20, "problematic simulator"). Thus, it is more plausible that the observed increment in SSQ total scores has a large component induced by VE immersion and a small component related to demand character of the SSQ administration. Nevertheless, we acknowledge that the design of this study cannot eliminate the possibility that the increase from baseline for the three test conditions is at least partially attributable to demand characteristics.

In addition to the main goal, we also performed some explorative analysis on whether people's baseline postural control ability may predict who is more likely to develop cybersickness in VR simulations, following a similar approach by Arcioni et al. (2018). Four measures of postural control were used as predictors, namely, COP and DFA along both AP and ML axes. However, in both experiments, none of these baseline postural measures could predict the SSQ scores in the speed profile conditions. These findings are generally consistent with those of Arcioni et al. (2018), who also showed little evidence that individual difference in baseline postural control is a reliable predictor of severity of cybersickness in VR.

We also observed a somewhat puzzling effect of COP movement between the AP and ML axes. In both experiments, normalized COP was significantly larger along the AP axis than the ML axis. The most natural explanation is that the simulated motion was much more prominent along the AP axis. However, this hypothesis can explain the results in Experiment 1, where the induced forward motion was indeed along the AP axis, but it cannot explain the data in Experiment 2, where the induced motion was circular and did not favor the AP axis. An alternative hypothesis is that due to the posture of the participants in the experiment, that is, with two feet apart along the ML axis, they were more stable along the ML axis than the AP axis, hence being more resistant to visually induced perturbations along the ML axis. Whether this hypothesis is true remains a topic for future research.

In summary, two experiments examined the effects of speed profiles on cybersickness for both linear and circular motions. The results provided no evidence for the common belief that constant speed is more comfortable than variable speed profiles for scenarios in typical VR applications. These findings have important implications for the design of locomotion techniques to traverse VR environments.

ACKNOWLEDGMENTS

This work was partially supported by NSF NRI grant nos. 1528036 and 1830639, EAGER grant no. 1548409, CONACyT post-doctoral fellowship 277028, and Catedras-CONACyT project 745. Steven LaValle is also affiliated with University of Oulu, Finland.

KEY POINTS

- Two experiments examined the hypothesis that constant speed is more comfortable than variable speed and may minimize cybersickness.
- Both experiments showed no significant difference in self-reported cybersickness between speed profiles and no convincing evidence for an effect of speed profile in terms of center of pressure displacement and detrended fluctuation analysis alpha values, for both linear and circular visual motions.
- These findings have important implications for the design of locomotion techniques involving traversal in virtual reality environments.

ORCID iD

Christopher Widdowson https://orcid.org/0000-0001-8614-6147

REFERENCES

Arcioni, B., Palmisano, S., Apthorp, D., & Kim, J. (2018). Postural stability predicts the likelihood of cybersickness in active HMD-based virtual reality. *Displays*, *58*, 3–11.

Bartlett, H. L., Ting, L. H., & Bingham, J. T. (2014). Accuracy of force and center of pressure measures of the Wii Balance Board. *Gait and Posture*, 39, 224–228.

Berg, K. O., Maki, B. E., Williams, J. I., Holliday, P. J., & Wood-Dauphinee, S. L. (1992). Clinical and laboratory measures of postural balance in an elderly population. *Archives of Physical Medicine and Rehabilitation*, *73*, 1073–1080.

Berthoz, A., Pavard, B., & Young, L. R. (1975). Perception of linear horizontal self-motion induced by peripheral vision (linear vection): Basic characteristics and visual-vestibular interactions. *Experimental Brain Research*, *23*, 471–489.

Bonnet, C. T., Faugloire, E., Riley, M. A., Bardy, B. G., & Stoffregen, T. A. (2006). Motion sickness preceded by unstable displacements of the center of pressure. *Human Movement Science*, 25, 800–820.

Bos, J. E., Bles, W., & Groen, E. L. (2008). A theory on visually induced motion sickness. *Displays*, *29*, 47–57.

Chang, C. H., Chen, F. C., Kung, W. C., & Stoffregen, T. A. (2017). Effects of physical driving experience on body movement and motion sickness during virtual driving. *Aerospace Medicine & Human Performance*, *88*, 985–992.

Cheung, B., Howard, I., & Money, K. (1991). Visually-induced sickness in normal and bilaterally labyrinthine-defective subjects. *Aviation Space and Environmental Medicine*, *62*, 527–531.

Clark, R. A., Bryant, A. L., Pua, Y., McCrory, P., Bennell, K., & Hunt, M. (2010). Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. *Gait and Posture*, *31*, 307–310.

Dorado, J. L., & Figueroa, P. (2014, March). *Ramps are better than stairs to reduce cybersickness in applications based on a HMD and a gamepad*. Paper presented at the IEEE Symposium on 3D User Interfaces (3DUI), Minneapolis, MN.

Gibson, J. J. (1958). Visually controlled locomotion and visual orientation in animals. *British Journal of Psychology*, *49*, 182–194.

Goldberger, A. L., Amaral, L. A. N., Glass, L., Hausdorff, J. M., Ivanov, P., Mark, R. G., . . . Stanley, H. E. (2000). PhysioBank, PhysioToolkit, and PhysioNet: Components of a new research resource for complex physiologic signals. *Circulation*, *101*, 215–220.

Gustavsen, M., Aamodt, G., & Mengshoel, A. M. (2006). Measuring balance in sub-acute stroke rehabilitation. *Advances in Physiotherapy*, *8*, 15–22.

Hu, S., Davis, M. S., Klose, A. H., Zabinsky, E. M., Meux, S. P., Jacobsen, H. A., . . . Gruber, M. B. (1997). Effects of spatial frequency of a vertically striped rotating drum on vection induced motion sickness. *Aviation Space and Environmental Medicine*, *68*, 306–311.

Hu, S., Stern, R. M., Vasey, M. W., & Koch, K. L. (1989). Motion sickness and gastric myoelectric activity as a function of speed of rotation of a circular vection drum. *Aviation Space and Environmental Medicine*, *60*, 411–414.

Jerald, J. (2015). *The VR Book: Human-centered design for virtual reality*. New York, NY: Association for Computing Machinery and Morgan & Claypool.

Kennedy, R. S., Drexler, J. M., Compton, D. E., Stanney, K. M., & Harm, D. L. (2001). Configural scoring of simulator sickness, cybersickness and space adaptation syndrome: Similarities and differences. In L. J. Hettinger & M. W. Haas (Eds.), *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp. 247–278). Mahwah, NJ: Lawrence Erlbaum.

Kennedy, R. S., & Fowlkes, J. E. (1992). Simulator sickness is polygenic and polysymptomatic: Implications for research. *The International Journal of Aviation Psychology*, *2*, 23–28.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, *3*, 203–220.

Kennedy, R. S., Lanham, D. S., Drexler, J. M., Massey, C. J., & Lilienthal, M. G. (1997). A comparison of cybersickness incidences, symptom profiles, measurement techniques, and suggestions for further research. *Presence: Teleoperators and Virtual Environments*, *6*, 638–644.

Kent, J. S., Hong, S. L., Bolbecker, A. R., Klaunig, M. J., Forsyth, J. K., O'Donnell, B. F., & Hetrick, W. P. (2012). Motor deficits in schizophrenia quantified by nonlinear analysis of postural sway. *PLoS ONE*, *7*, e0041808.

Keshavarz, B., Hecht, H., & Lawson, B. D. (2014). Visually-induced motion sickness: Causes, characteristics, and countermeasures. In K. M. Stanney & K. S. Hale (Eds.), *Handbook of virtual environments: Design, implementations, and applications* (pp. 648–681). Boca Raton, FL: CRC Press.

Keshavarz, B., Riecke, E. R., Hettinger, L. J., & Campos, J. L. (2015). Vection and visually induced motion sickness: How are they related? *Frontiers in Psychology, 6*, Article 472.

Kirk, R. E. (2013). *Experimental design: Procedures for the behavioural sciences* (4th ed.). Thousand Oaks, CA: SAGE.

Kolasinski, E. M. (1995). *Simulator sickness in virtual environments* (No. ARI Technical Report 1027). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

LaValle, S. M. (2016). *Virtual reality*. Retrieved from http://vr.cs.uiuc.edu/vrbook.pdf

LaViola, J. J. (2000). A discussion of cybersickness in virtual environments. *ACM SIGCHI Bulletin*, *32*, 47–56.

Li, R., Walter, H., Curry, C., Rath, R., Peterson, N., & Stoffregen, T. A. (2018). Postural time-to-contact as a precursor of visually induced motion sickness. *Experimental Brain Research*, *236*, 1631–1641.

McCauley, M. E., & Sharkey, T. J. (1992). Cybersickness perception of self-motion in virtual environments. *Presence*, *1*, 311–318.

Morasso, P. G., Spada, G., & Capra, R. (1999). Computing the COM from the COP in postural sway movements. *Human Movement Science*, *18*, 759–767.

Nooij, S. A. E., Pretto, P., Oberfeld, D., Hecht, H., & Bülthoff, H. H. (2017). Vection is the main contributor to motion sickness induced by visual yaw rotation: Implications for conflict and eye movement theories. *PLoS ONE*, *12*, e0175305.

Palmisano, S., Allison, R. S., Schira, M. M., & Barry, R. J. (2015). Future challenges for vection research: Definitions, functional significance, measures, and neural bases. *Frontiers in Psychology, 6*, Article 193.

Park, D.-S., & Lee, G. (2014). Validity and reliability of balance assessment software using the Nintendo Wii balance board: Usability and validation. *Journal of NeuroEngineering and Rehabilitation, 11*, Article 99.

Peng, C.-K., Havlin, S., Stanley, H. E., & Goldberger, A. L. (1995). Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. *Chaos*, *5*, 82–87.

Reason, J., & Brand, J. J. (1975). *Motion sickness*. London, England: Academic Press.

Rebenitsch, L., & Owen, C. (2016). Review on cybersickness in applications and visual displays. *Virtual Reality*, *20*, 101–125.

Scoppa, F., Capra, R., Gallamini, M., & Shiffer, R. (2013). Clinical stabilometry standardization. Basic definitions—Acquisition interval—Sampling frequency. *Gait and Posture*, *37*, 290–292.

Smart, L. J., Jr., Stoffregen, T. A., & Bardy, B. G. (2002). Visually induced motion sickness predicted by postural instability. *Human Factors*, *44*, 451–465.

So, R., Ho, A., & Lo, W. (2001). A metric to quantify virtual scene movement for the study of cybersickness: Definition, implementation, and verification. *Presence: Teleoperators and Virtual Environments*, *10*, 193–215.

So, R. H. Y., Lo, W. T., & Ho, A. T. K. (2001). Effects of navigation speed on motion sickness caused by an immersive virtual environment. *Human Factors*, *43*, 452–461.

Stanney, K. M., Kennedy, R. S., & Drexler, J. M. (1997). Cybersickness is not simulator sickness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *2*, 1138–1142.

Stoffregen, T. A., Chang, C. H., Chen, F. C., & Zeng, W. J. (2017). Effects of decades of physical driving on body movement and motion sickness during virtual driving. *PLoS ONE*, *12*, e0187120.

Stoffregen, T. A., Chen, F. C., Varlet, M., Alcantara, C., & Bardy, B. G. (2013). Getting your sea legs. *PLoS ONE*, *8*, e66949.

Stoffregen, T. A., Faugloire, E., Yoshida, K., Flanagan, M., & Merhi, O. (2008). Motion sickness and postural sway in console video games. *Human Factors*, *50*, 322–331.

Tinetti, M. E. (1986). Performance-oriented assessment of mobility problems in elderly patients. *Journal of the American Geriatrics Society*, *34*, 119–126.

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & Posture*, *3*, 193–214.

Yang, S., & Sheedy, J. (2011). Effects of vergence and accommodative responses on viewer's comfort in viewing 3D stimuli. In *Proceedings of SPIE: Stereoscopic Displays and Applications XXII* (Vol. 7863). Retrieved from https://spie.org/Publications/Proceedings/Paper/10.1117/12.872546?SSO=1

Young, S. D., Adelstein, B. D., & Ellis, S. R. (2006). Demand characteristics of a questionnaire used to assess motion sickness in a virtual environment. In *Proceedings of IEEE virtual reality conference* (pp. 97–102). Retrieved from https://ieeexplore.ieee.org/document/1667632

Christopher Widdowson is a PhD student in the Department of Psychology at the University of Illinois at Urbana–Champaign. He received a master of science degree in experimental psychology from the University of Texas at San Antonio in 2014.

Israel Becerra is a postdoctoral researcher at the Centro de Investigación en Matemáticas. He received a bachelor's degree in mechatronics, robotics, and automation engineering from the Monterrey Institute of Technology and Higher Education in 2007 and a master's and PhD in computer science from the Centro de Investigación en Matemáticas in 2010 and 2015, respectively.

Cameron Merrill is a PhD student in the Department of Computer Science at the University of Illinois at Urbana–Champaign. He received a bachelor's degree in computer science from Michigan State University in 2016.

Ranxiao Frances Wang received her PhD from Massachusetts Institute of Technology in 1999 in computational cognitive sciences and is a professor in the Department of Psychology and Beckman Institute at the University of Illinois. Her research focuses on visual and spatial cognition, human–robot interaction, and attention and cognitive control.

Steven LaValle received his BS, MS, and PhD degrees in electrical and computer engineering at the University of Illinois at Urbana–Champaign in 1990, 1993, and 1995, respectively. He is a professor at the University of Oulu at the Center for Ubiquitous Computing, Faculty of Information Technology and Electrical Engineering.

Date received: July 16, 2018
Date accepted: August 26, 2019