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ARTICLE

Postural precursors of motion sickness in head-mounted displays: drivers and passengers, women and men

Christopher Curry, Nicolette Peterson, Ruixuan Li and Thomas A. Stoffregen

School of Kinesiology, University of Minnesota, Minneapolis, MN, USA

ABSTRACT

Motion sickness is preceded by distinctive patterns of postural activity that differ between the sexes. We asked whether such postural precursors of motion sickness might exist before participants were exposed to a virtual driving game presented via a head-mounted display. Men and women either controlled a virtual vehicle (drivers), or viewed a recording of virtual vehicle motion (passengers). Before exposure to the game, we recorded standing body sway while participants performed simple visual tasks (staring at a blank page vs. counting target letters in a block of text). Following game exposure, participants were classified into Well and Sick groups. In a statistically significant interaction, the multifractality of body sway varied as a function of sex, vehicle control, and motion sickness status. The results confirm that postural precursors of motion sickness differ between the sexes, and extend these to the control of virtual vehicles in head-mounted displays.

Practitioner Summary: We asked whether postural sway might predict motion sickness during exposure to a driving game via a head-mounted display. Participants drove a virtual car (drivers), or watched recorded car motion (passengers). Beforehand, we measured standing body sway. Postural precursors of motion sickness differed between the sexes and drivers and passengers.

Abbreviations: M: meters; SD: standard deviation; kg: kilograms; COP: centre of pressure; AP: anterior-posterior; ML: mediolateral; cm: centimeters; s: seconds; min: minutes; MF: DFA: multifractal detrended fluctuation analysis; DFA: detrended fluctuation analysis; ANOVA: analysis of variance; CI: confidence interval; Hz: hertz; SE: standard error of the mean

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Introduction

Motion sickness is preceded by distinctive patterns of postural sway. That is, postural sway differs between persons who (later) report motion sickness, and those who do not. Such differences have been identified in postural sway during exposure to potentially nauseogenic motion stimulation (e.g. Bonnet et al. 2006; Stoffregen and Smart 1998). More relevant for the present study is the finding of such differences in postural sway before participants were exposed to stimulus motion of any kind (e.g. Arcioni et al. 2019; Koslucher, Haaland, and Stoffregen 2016; Munafo et al. 2016; Palmisano, Arcioni, and Stapley 2018; Risi and Palmisano 2019; Stoffregen et al. 2013; Stoffregen et al. 2000; Stoffregen and Smart 1998; Stoffregen et al. 2010). In the present study, we asked how postural precursors of motion sickness might be influenced by co-variation of an intrinsic factor (sex) and an extrinsic factor (control of a virtual vehicle).

Sex-specific postural precursors of motion sickness

Susceptibility to motion sickness differs between women and men. This is true (e.g. Lawther and Griffin, 1986), and in cases of virtual displacement, such as interactive video games (e.g. Munafo et al. 2016). Interestingly, there also are characteristic sex differences in the quantitative kinematics of body sway (e.g. Anton, Ernst, and Basta 2019; Era et al. 2006; Kim et al. 2010). Taken together, these literatures suggest the possibility that sex differences in susceptibility to motion sickness might be related to sex differences in the control of the body. Recent evidence is consistent with this idea.

Koslucher, Haaland, and Stoffregen (2016) exposed standing participants to imposed oscillation of the illuminated environment (a moving room). Motion sickness incidence was greater among women (38%) than among men (9%). Prior to movement of the room, the researchers measured standing body sway (on a force plate) in the absence of any motion stimuli, while

CONTACT Thomas A. Stoffregen tas@umn.edu School of Kinesiology, University of Minnesota, 1900 University Ave SE, Minneapolis, MN 55455, USA

participants performed one of two simple visual tasks. Analysis of the positional variability of the body's centre of pressure revealed a statistically significant interaction between sex, the two visual tasks, and later membership in the Well and Sick groups.

Munafo et al. (2016) conducted a similar evaluation of pre-exposure body sway during performance of simple visual tasks. However, in their study, measurement of body sway was followed by exposure to an interactive (i.e. user-controlled) video game presented via a head-mounted display. When the video game included virtual locomotion (their Experiment 2), the incidence of motion sickness was greater among women (78%) than among men (33%). Analysis of positional variability of the centre of pressure during pre-exposure stance again revealed a statistically significant, 3-way interaction between sex, visual tasks, and later membership in the Well and Sick groups.

Sex differences in postural precursors of motion sickness have not been incremental. Rather, in both the studies of Koslucher, Haaland, and Stoffregen (2016) and Munafo et al. (2016), male and female postural precursors of motion sickness differed qualitatively.

Postural precursors and the driver-passenger effect

In automobiles, motion sickness is more common among passengers than among drivers. This common anecdotal report has been verified in controlled laboratory research using purpose-built whole-body motion devices (e.g. Rolnick and Lubow 1991). The same effect occurs in the context of virtual motion: In Dong, Yoshida, and Stoffregen (2011), seated participants either controlled (drivers) or merely watched (passengers) a driving video game. By a factor of four, the incidence of motion sickness was greater among passengers.

Dong, Yoshida, and Stoffregen (2011) monitored the kinematics of the head and torso during exposure to the driving game. Analyses of these data revealed postural precursors of motion sickness for both drivers and passengers. In addition, Dong, Yoshida, and Stoffregen (2011) found that movement of the head and torso differed between drivers and passengers. The temporal dynamics of head and torso movement differed between drivers and passengers. Perhaps surprisingly, despite the finding that motion sickness was more common among passengers than among drivers, analysis of the spatial magnitude of movement revealed that drivers moved more than passengers.

The present study

Curry et al. (2020) studied motion sickness among participants exposed to a driving video game presented through a head-mounted display. Using the yoked-control method of Dong, Yoshida, and Stoffregen (2011), half of participants (Drivers) controlled the virtual vehicle, while the other half (Passengers) did not control the virtual vehicle. This manipulation was crossed with an equal variation in sex: Half of both the Driver and Passenger groups were women, while the other half were men. The overall incidence of motion sickness was comparable to previous studies (e.g. Munafo et al. 2016). Curry et al. (2020) found no differences in motion sickness incidence or severity between the sexes, or between drivers and passengers (for interpretation of these potentially anomalous findings, see Curry et al. 2020). The data reported by Curry and colleagueas were part of a larger study of sex differences and the driver-passenger effect in head-mounted displays. In the present article, we report data on postural sway and visual performance that were collected from the same participants, as part of that larger study.

Previous research has demonstrated that postural precursors of motion sickness differ between women and men (Koslucher, Haaland, and Stoffregen 2016; Munafo et al. 2016). In the present study, we asked whether sex-specific postural precursors of motion sickness might, themselves differ between drivers and passengers in driving games presented via a head-mounted display system.

Historically, human movement has often been evaluated in terms of spatial magnitude (e.g. the standard deviation of position, of the length, or area of postural sway). Such measures commonly lead to definitions of movement stability in which greater magnitude is equated with less stability (e.g. Reed-Jones et al. 2008). Dynamic systems theory has motivated a qualitative shift in measures of animate movement, and in concepts of stability and instability of movement (e.g. Stergiou and Decker 2011). Measures of the temporal dynamics of movement differ qualitatively from measures of spatial magnitude (e.g. Lin et al. 2008; Riccio and Stoffregen 1988). Postural precursors of motion sickness can exist in the temporal dynamics of sway (e.g. Stoffregen et al. 2010), as well as in its spatial magnitude (e.g. Stoffregen and Smart 1998), and the degree of multifractality of the postural time series (e.g. Koslucher, Munafo, and Stoffregen 2016; Munafo et al. 2016). In the present study, we evaluated two orthogonal measures of standing body sway. We evaluated the spatial magnitude of sway in terms of the positional variability of the body (e.g. Bonnet et al. 2006; Stoffregen et al. 2013).

We also evaluated the degree of multifractality in sway. The analysis of multifractality in human movement is relatively novel, and researchers have stated it is not entirely clear how variations in multifractality should be interpreted (Kelty-Stephen et al. 2013). More broadly, there is ongoing debate about the nature of stability and instability in animate movement (e.g. Riccio 1993; Stergiou and Decker 2011). The postural instability theory (Riccio and Stoffregen 1988) can help us to interpret multifractality in postural sway. Postural instability theory dictates that patterns of sway among participants who will become sick are less stable; hence, differences in multifractality between the Well and Sick groups correspond to variations in postural stability. Koslucher, Munafo, and Stoffregen (2016) and Li et al. (2018), found that motion sickness was preceded by variations in multifractality that were not observed among participants who did not become sick. In the present study, we asked whether differences between Well and Sick participants in the multifractality of standing body sway might be modulated by sex, and/or by participants' status as Drivers versus Passengers during subsequent exposure to a virtual vehicle.

Method

Participants

A total of 79 individuals participated (41 women and 38 men), in exchange for course credit. Participants ranged in age from 18 to 49 years (mean = 21.84 years, SD = 4.19 years), in height from 1.51 to 1.94 m (mean = 1.72 m, SD = 0.10 m), and in weight from 47.63 to 104.33 kg (mean = 71.58 kg, SD = 12.47 kg). The research protocol was approved in advance by the IRB of the University of Minnesota.

Apparatus

We used the Oculus Rift CV1. The device comprised a lightweight (0.360 kg) headset that completely covered the field of view. The headset included separate displays for each eye, each with 1080 × 1020 resolution, yielding a 100° horizontal field of view. A lens located in front of each display rendered display content at optical infinity.

Data on postural activity were obtained using a force plate (AccuSway Plus; AMTI, Watertown, MA). We collected displacement of the centre of pressure (COP) in the anterior-posterior (AP) and mediolateral (ML) axes at 50 Hz.

Procedure

Each participant gave informed consent and was informed they could discontinue at any time without penalty. Following previous studies (e.g. Dong, Yoshida, and Stoffregen 2011; Kosluchei et al. 2015; Merhi et al. 2007; Stoffregen et al. 2008, 2010; Stoffregen and Smart 1998), we separately assessed the incidence of motion sickness and the severity of symptoms (for details, see Curry et al. 2020). Participants were instructed (both verbally and on the consent form) to discontinue the experiment immediately if they experienced any motion sickness symptoms, however mild.

For postural testing, participants removed their shoes and were measured for height and weight, after which they stood on the force plate, which was located 1 m from a wall. Participants stood on marked lines on the plate such that their heels were 17 cm apart with an angle of 10° between the feet. While standing on the force plate, each participant completed a single trial in an Inspection task and one in a Search task. The visual tasks were similar to those used by Munafo et al. (2016), and Stoffregen et al. (2000). Targets consisted of sheets of white paper 21.6 cm × 27.9 cm, mounted on rigid cardboard. Targets for the Inspection and Search tasks were 1.0 m in front of the heels, affixed to a white wall and adjusted to each participant's eye height. In the Inspection task, the target was a blank sheet of white paper. There was not a single fixation point: Participants were instructed to keep their gaze within the boundary of the target. In the Search task, the target was a block of English text, comprising 14 lines of text printed in a 12-point sans serif font, which was affixed to an otherwise blank card. In the Search task, the participant was asked to count the number of times the letter, *r*, appeared in the block of text. At the end of each Search trial, the participant reported the number of letters counted and their position in the text at the end of the trial. Each trial was 60 s in duration. The Inspection and Search tasks were presented in alternating order. Odd-numbered participants began with the Search task, while even-numbered participants began with the Inspection task.

After performing the visual tasks while standing, participants sat on the stool, donned the Oculus headset, and were exposed to *Assetto Corsa,* a commercial driving game. Each Driver drove a Ferrari 458 Italia on the Highlands Long Track. Details of the driving game were reported in Curry et al. (2020). During exposure to the video game, we used a between-participants, yoked control design, with individual Passengers yoked to individual Drivers. Participants played or viewed the game for up to 15 min. Data on head and torso motion were collected continuously throughout the game session; these data will be reported elsewhere. Additional details of the yoked-control procedure are reported in Curry et al. (2020).

After completing the 15-min game exposure, or after discontinuation (whichever came first), we assessed motion sickness incidence and severity.

Analysis of postural sway

We separately evaluated the spatial magnitude and multifractality of centre of pressure positions. We evaluated the spatial magnitude of postural activity in terms of positional variability, which we defined operationally as the standard deviation of centre of pressure positions. We evaluated the multifractality of postural activity using multifractal detrended fluctuation analysis, MF-DFA (e.g. Ihlen et al. 2013; Munafo et al. 2016). MF-DFA is an extension of more traditional detrended fluctuation analysis, or DFA (Lin et al. 2008). MF-DFA has been used in the assessment of postural sway in a variety of contexts (e.g. Fink et al. 2019; Munafo et al. 2016). Traditional DFA assumes that fluctuations in a time series are homogeneous (Ihlen and Vereijken 2010). Multifractal fluctuations are interdependent and heterogeneous. The range of the singularity exponent, $h(q)$, indicates the heterogeneous nature of multifractal fluctuations (Ihlen 2012). The width of this range can be used as an index of the degree (or amount) of multifractality in a time series. The range of $h(q)$ values is known as the *singularity spectrum*, or simply the *spectrum*. The wider the multifractal spectrum, the more multifractal is the movement (Kelty-Stephen et al. 2013). We conducted inferential statistics on the width of the singularity spectrum for each trial. We conducted MF-DFA using open source code for MATLAB (MFDFA1; Ihlen 2012). We selected a minimum scaling range of 16 data points with 19 evenly spaced increasing segment sizes to a maximum of the length of the time series. This range was the same for each time series. Use of the range of $h(q)$ to estimate spectrum width is susceptible to outliers (Ihlen 2012; cf. Kelty-Stephen et al. 2013). For this reason, before conducting ANOVA on spectrum width we removed data from participants for whom spectrum width was greater than three standard deviations from the overall mean (across trials and participants).

There were 3000 data points in each time series. We conducted separate ANOVAs on positional variability and the width of the multifractal spectrum. For each ANOVA, the factors were Body Axis (AP vs. ML), Visual Task (Inspection vs. Search), Sex (Women vs. Men), Control (Drivers vs. Passengers), and Sickness Groups (Well vs. Sick). Body Axis and Visual Task were within-participants factors, while Sex, Control, and Sickness Groups was a between-participants factor.

Results

As reported by Curry et al. (2020), the overall incidence of motion sickness was 43% (34/79). Motion sickness incidence did not differ between Drivers and Passengers, or between women and men. Data on exposure duration (i.e. time of discontinuation) and symptom severity were reported by Curry et al. (2020).

Search task performance

Before exposure to the head-mounted display, standing participants performed the Inspection and Search tasks. We did not evaluate performance on the Inspection task. Following previous studies (e.g. Koslucher, Haaland, and Stoffregen 2016; Stoffregen et al. 2000), we assumed that participants were able to maintain their gaze within the borders of the card. Performance on the Search Task was evaluated in terms of percent correct, which we computed as the number of times the target letter was counted divided by the total number of target letters in the stimulus text, and by reading speed, which we computed as the number of words counted during the trial divided by the duration of the trial. Overall, participants counted 72.63% (SD = 0.18) of the target letters. We used independent sample *t*-tests to evaluate differences in reading accuracy between the sexes, between Drivers and Passengers, and between the Well and Sick groups. There were no significant effects.

We evaluated reading speed using a 2 (Women vs. Men) × 2 (Driver vs. Passenger) × 2 (Well vs. Sick) ANOVA. The Sex × Driver-Passenger interaction was significant, $F(1, 71) = 9.24$, $p = .003$, partial $\eta^2 = .115$ (Figure 1). Post-hoc tests (95% confidence intervals) revealed that reading speed differed between Drivers and Passengers for men, but not for women.

Positional variability

For the positional variability of the centre of pressure, the main effect of Body Axis was significant, $F(1, 71) = 216.47$, $p < .001$, partial $\eta^2 = .75$. Positional variability in the AP axis (mean = 0.390 cm, SE = 0.018 cm) was

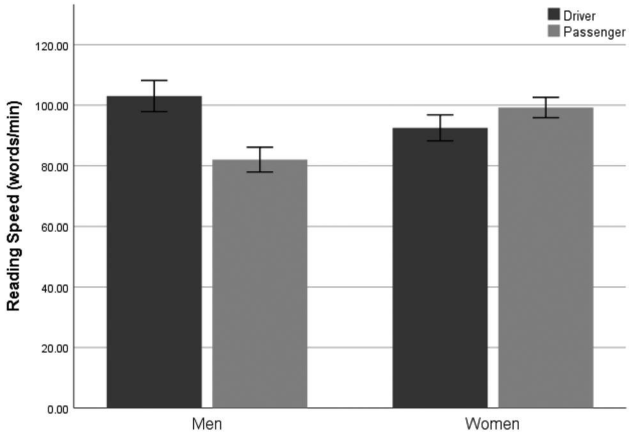

Figure 1. Reading speed (words/min) during performance of the Search task, illustrating the statistically significant interaction between sex and vehicle control. The error bars represent one standard error of the mean.

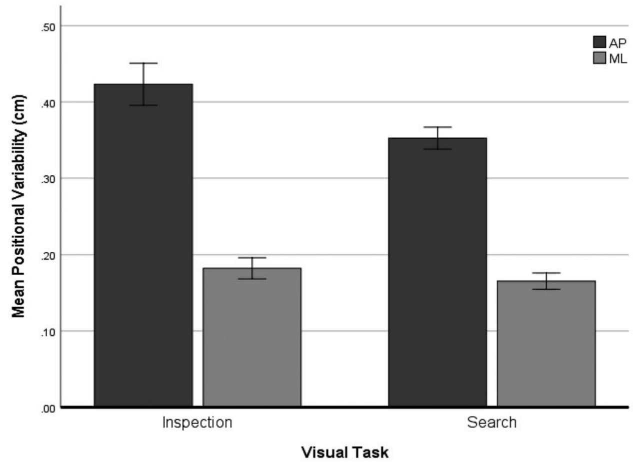

Figure 2. Positional variability of the Centre of Pressure, illustrating the statistically significant interaction between Body Axis (AP vs. ML) and Visual Task (Inspection vs. Search). The error bars represent one standard error of the mean.

greater than in the ML axis (mean = 0.174 cm, SE = 0.010 cm). In addition, the main effect of Visual Task was significant, $F(1, 71) = 4.38$, $p = .04$, partial $\eta^2 = .06$. Positional variability during performance of the Inspection task (mean = 0.303 cm, SE = 0.020 cm) was greater than during performance of the Search task (mean = 0.261 cm, SE = 0.01 cm). Finally, the Body Axis × Visual Task interaction was significant, $F(1, 71) = 6.03$, $p = .016$, partial $\eta^2 = .08$ (Figure 2). There were no other significant effects.

Width of the multifractal spectrum

One participant was identified as an outlier, and so was excluded from our analysis of the width of the multifractal spectrum. The main effect of Body Axis was significant, $F(1, 70) = 12.96$, $p = .001$, partial $\eta^2 = .16$. The multifractal spectrum was wider for postural activity in the AP axis (mean = 0.51, SE = 0.01) than in the ML axis (mean = 0.46, SE = 0.01). The main effect of Visual Tasks was significant, $F(1, 70) = 17.63$, $p < .001$, partial $\eta^2 = .20$. The multifractal spectrum was wider for postural activity during performance of the Inspection task (mean = 0.52, SE = 0.01) than during performance of the Search task (mean = 0.45, SE = 0.01). The main effect of Sex was significant, $F(1, 70) = 11.56$, $p = .001$ partial $\eta^2 = .142$. The multifractal spectrum was wider for the postural activity of men (mean = 0.51, SE = 0.01) than women (mean = 0.45, SE = 0.01). The interaction between Body Axis and Sickness Groups was significant, $F(1, 70) = 6.19$, $p = .015$, partial $\eta^2 = .08$ (Figure 3). The 95% confidence intervals revealed that the difference between the AP and ML axes was significant for the Well group (AP Mean = 0.52, SD = 0.1, 95% CI [0.50–0.56]; ML Mean = 0.44, SD = 0.02, 95% CI [0.41–0.47]), but not for the Sick group. Finally, the Sex × Sickness Groups × Control interaction was significant, $F(1, 70) = 4.14$, $p = .046$, partial $\eta^2 = .05$ (Figure 4). The 95% confidence intervals revealed that for sick women, Drivers (mean = 0.486, SD = 0.03, 95% CI [0.44–0.54]) and Passengers (mean = 0.40, SD = 0.03, 95% CI [0.34–0.46]) differed. In addition, for sick female passengers, spectrum width was reduced relative to well male drivers (mean = 0.53, SD = 0.03, 95% CI [0.48–0.58]) and sick male passengers (mean = 0.53, SD = 0.03, 95% CI [0.47–0.59]). In addition, for sick male Passengers (mean = 0.53, SD = 0.03, 95% CI [0.47–0.59]) spectrum width differed from well female Drivers (mean = 0.46, SD = 0.03, 95% CI [0.41–0.50])

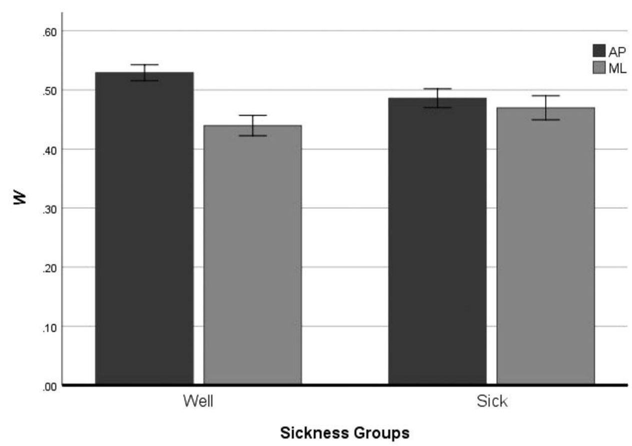

Figure 3. Width, W, of the multifractal spectrum, illustrating the statistically significant interaction between Body Axis (AP vs. ML) and Sickness Groups (Well vs. Sick). The error bars represent one standard error of the mean.

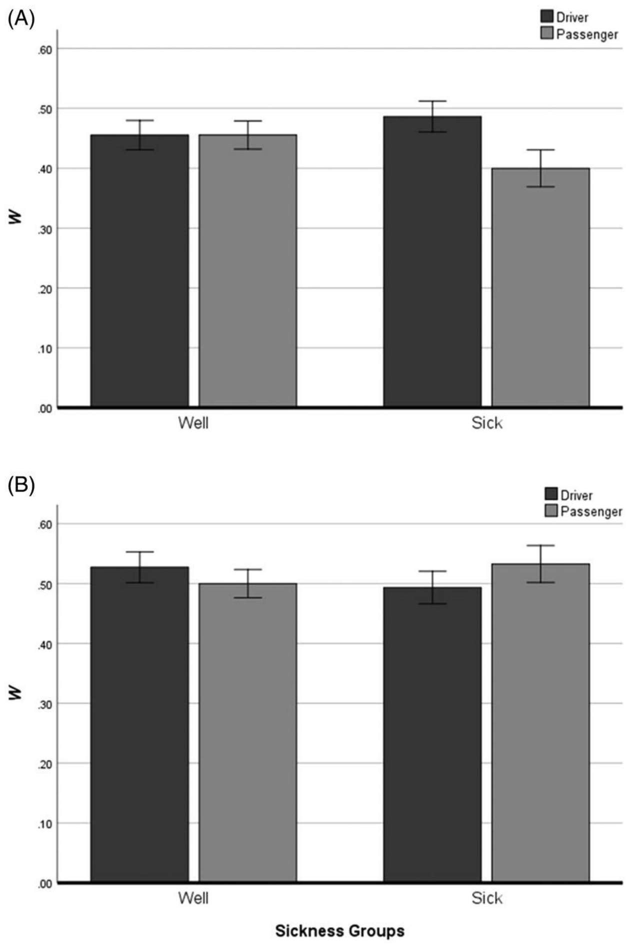

Figure 4. Width, W, of the multifractal spectrum, illustrating the statistically significant interaction between Vehicle Control (Drivers vs. Passengers), Sex (Women vs. Men) and Sickness Groups (Well vs. Sick). (A) Women; (B) men. The error bars represent the standard error of the mean.

and well female Passengers (mean = 0.46, SD = 0.02, 95% CI [0.41–0.50]). There were no other significant effects.

Discussion

We monitored standing body sway as participants performed simple visual tasks, in one of which participants counted designated target letters in a block of text. After completion of the standing visual tasks, participants were exposed to a virtual driving game presented via a head-mounted display. In a yoked-control design, half the participants drove the virtual vehicle (Drivers), while the other half merely watched prerecorded vehicle motion (Passengers). Drivers and Passengers were evenly divided between women and men. In the letter counting task, reading speed differed between women and men as a function of their future status as Drivers or Passengers. As reported by Curry et al. (2020), exposure to the virtual vehicle led to motion sickness in some participants. We analysed standing body sway for differences between Drivers and Passengers, women and men, and Well and Sick groups. We replicated common effects of visual tasks on the kinematics of standing body sway, and confirmed that sway differed between the sexes. In addition, we identified statistically significant differences between the Well and Sick groups. Because data on standing body sway were collected before participants were exposed to the virtual vehicle, these interactions reveal postural precursors of visually induced motion sickness. We discuss these results in turn.

Reading speed

While standing, participants performed the Inspection and Search tasks. Several studies have shown that postural activity differs during performance of these two visual tasks (Stoffregen et al. 2000). Our primary purpose in assessing performance on the Search tasks was to verify that participants actually performed the tasks. Previous studies of postural precursors of motion sickness have assessed postural activity during performance of the same Inspection and Search tasks. This manipulation sometimes has revealed sex differences in visual performance. For example, Koslucher, Haaland, and Stoffregen (2016), found that women read more rapidly than men. In the present study, we found that sex differences in reading speed differed between participants assigned to the Driver versus Passenger groups (Figure 1). The 95% confidence intervals revealed that reading speed differed between Drivers and Passengers among men, but not among women. One way to interpret this effect is that overall between-participants reading speed was more variable among men than women. Sex differences have been reported in several cognitive abilities, such as verbal and quantitative reasoning. Interestingly, while researchers have found sex differences in mean scores, in some cases they also have found statistically significant sex differences in the between-participants variability of scores, with variability being greater among males than females (e.g. Strand, Deary, and Smith 2006). The present result is consistent with such effects.

Postural effects independent of motion sickness

We identified several statistically significant effects in postural activity that were independent of motion sickness status. While not relevant to the existence of postural precursors of motion sickness, these effects, as replications, are important as validity cheques for our manipulations. The main effects of body axis, in both positional variability and the width of the multifractal spectrum, replicated a common finding (e.g. Balasubramaniam, Riley, and Turvey 2000; Munafo et al. 2016; Winter et al. 1996). Similarly, the main effects of visual tasks, in both positional variability and the width of the multifractal spectrum also replicated a common finding (e.g. Koslucher et al. 2012; Prado, Stoffregen, and Duarte 2007; Stoffregen et al. 2000; Yu et al. 2013). For positional variability, the interaction between these factors (Figure 2) reflected the fact that the Search task constrained postural sway more in the AP axis than in the ML axis, as has been reported in previous studies (e.g. Izquierdo-Herrera et al. 2018; Koslucher et al. 2012). Many studies have reported that the kinematics of standing body sway differ between the sexes. In previous research, sex differences have been observed in both the spatial magnitude and the temporal dynamics of standing body sway (e.g. Era et al. 2006; Kim et al. 2010). Our finding of a sex difference in the width of the multifractal spectrum appears to be novel.

Taken together, we observed several statistically significant effects that were independent of the occurrence of motion sickness. Each of these effects replicated effects observed in previous studies conducted in different laboratories using a wide range of specific manipulations and dependent variables. Accordingly, our replication of these effects suggests that our sample was representative, and that our manipulations were compatible with the existing literature.

Postural precursors of motion sickness

In evaluating sway before participants were exposed to any stimulus motion, we found no evidence for postural precursors of motion sickness in the positional variability of the COP. Researchers often have found postural precursors of motion sickness in measures of the spatial magnitude of postural sway, such as positional variability (e.g. Arcioni et al. 2019; Koslucher et al. 2014; Koslucher, Haaland, and Stoffregen 2016; Munafo et al. 2016; Palmisano, Arcioni, and Stapley 2018; Stoffregen and Smart 1998; Villard et al. 2008; Weech, Varghese, and Barnett-Cowan 2018). However, some studies have not found postural precursors of motion sickness in measures of the spatial magnitude of sway (e.g. Dennison and D'Zmura 2017; Li et al. 2018; Palmisano, Arcioni, and Stapley 2018; Stoffregen et al. 2013). The postural instability theory of motion sickness (Riccio and Stoffregen 1988) predicts that postural precursors of motion sickness will exist; however, Riccio and Stoffregen stated explicitly that these precursors need not exist in measures of the spatial magnitude of sway, such as the positional variability of the COP. Contrary to subsequent mis-interpretations (e.g. Dennison and D'Zmura 2017), Riccio and Stoffregen did not define stability and instability solely in terms of the spatial magnitude of movement. That is, they did not predict that individuals who later became motion sick would sway *more* than individuals who did not become sick. Consistent with this position of Palmisano et al. (2018, 326) noted, 'it is possible then that reanalysis of this postural data using … non-linear analyses … might uncover relationships that would not otherwise be observable'. It is in part for this reason that we evaluated multiple, orthogonal measures of postural sway.

For the width of the multifractal spectrum, we found two interactions that included the Sickness Groups variable. First, the interaction between Sickness Groups and Body Axis was statistically significant (Figure 3). The 95% confidence intervals revealed that spectrum width differed between the AP and ML axes for the Well group, but not for the Sick group. That is, the variation between body axes that characterised postural sway in the Well group was absent among those who (later) reported motion sickness. The absence of axis-specific multifractality can be interpreted as an absence of axis-specific control of posture (e.g. Balasubramaniam, Riley, and Turvey 2000). If axis-specific control characterises stable control of posture, then the absence of axis-specific control can be interpreted as a form of unstable control, consistent with the postural instability theory of motion sickness.

We also found a statistically significant 3-way interaction between sex, driving status, and sickness groups (Figure 4). That is, postural precursors of motion sickness differed between the sexes as a function of their future role in the video game; active control (Drivers) versus passive observation (Passengers) of the motion of a virtual vehicle. Our results support the hypothesis that the postural precursors of motion sickness may be unique to each individual (e.g. men vs. women) and may vary with changes in task dynamics (e.g. driver vs. passenger); (cf. Slowinski et al. 2016).

Our identification of postural precursors of motion sickness before participants were exposed to any stimulus motion is consistent with previous studies in which postural precursors of motion sickness have been identified prior to sea travel (Stoffregen et al. 2013), and before exposure to laboratory motion devices (e.g. Palmisano, Arcioni, and Stapley 2018; Stoffregen and Smart 1998), and head-mounted displays (Arcioni et al. 2019; Munafo et al. 2016; Risi and Palmisano 2019). The finding that sway differed between participants as a function of their subsequent role in the experiment (Drivers vs. Passengers) is novel. The effect might be regarded as a spurious result of random assignment. However, the effect also could reflect actual variations arising from long-term experience. Stoffregen et al. (2017) evaluated postural precursors of motion sickness while driving a virtual vehicle. They compared middle-aged adults with versus without decades of experience driving physical vehicles. While driving a virtual vehicle, postural precursors of motion sickness differed between participants as a function of whether they had experience driving physical vehicles. Stoffregen et al. interpreted this effect as reflecting constraints on control of the body (within physical vehicles) that differ between drivers and passengers. The effect reported by Stoffregen et al. together with the effect illustrated in Figure 4 may be related to the developing consensus that the definition of postural activity is not general, or context-independent, but varies across tasks and situations (e.g. Haddad et al. 2013; Riccio and Stoffregen 1988).

Conclusion

We evaluated standing body sway before participants were exposed to a virtual vehicle presented via a head-mounted display. During stance, the multifractality of sway differed between participants who (later) became sick and those who did not. We found that postural precursors of motion sickness were influenced by co-variation of an intrinsic factor (sex) and an extrinsic factor (control of a virtual vehicle). These results are consistent with the general prediction of the postural instability theory of motion sickness (Riccio and Stoffregen 1988) that the kinematics of movement should differ between individuals who become motion sick and those who do not, and that differences in movement should exist before the onset of subjective symptoms. The effects that we observed are consistent with effects reported in the context of sex (e.g. Koslucher, Haaland, and Stoffregen 2016), and in research comparing individuals with versus without experience controlling physical vehicles (Chang et al. 2017; Stoffregen et al. 2017). Overall, the results are consistent with the postural instability theory of motion sickness, and indicate that postural precursors of motion sickness can be influenced by both intrinsic and extrinsic factors.

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Data availability statement

The data regarding the article is available online at https://conservancy.umn.edu/handle/11299/209152

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