Published in final edited form as:
Hum Factors. 2008 April ; 50(2): 332–345.

Postural Instability and Motion Sickness in a Virtual Moving Room

Sébastien J. Villard, **Moira B. Flanagan**, **Gina M. Albanese**, and **Thomas A. Stoffregen**
University of Minnesota, Minneapolis, Minnesota

Abstract

Objective—We examined motion sickness in an oscillating virtual environment presented via a video projector system.

Background—Visible oscillation of the physical environment is known to induce both postural instability and motion sickness, but it cannot be assumed that the same phenomena will occur in a virtual simulation of such motion.

Method—Standing participants (3 men and 9 women, 20–22 years of age) were exposed to oscillation of a virtual room. The stimulus was a computer-generated simulation of a laboratory device that is known to induce postural instability and motion sickness. Participants viewed the simulation for up to 40 min and were instructed to discontinue if they experienced symptoms of motion sickness.

Results—Motion sickness incidence (42%) did not differ from that in studies using the corresponding physical moving room. Prior to motion sickness onset, the sick group exhibited changes in movement, relative to the well group, as predicted by the postural instability theory of motion sickness. Differences in movement between the sick and well groups developed over time, in contrast with previous studies using physical moving rooms, in which such movement differences have not evolved.

Conclusion—The results indicate that changes in postural activity precede motion sickness that is induced by an oscillating virtual environment, but they also reveal differences in postural responses to virtual and physical motion environments.

Application—Potential applications of this research include recommendations for the use of virtual environments as models for perception and action in physical environments.

INTRODUCTION

Motion sickness occurs in a variety of domains, including laboratory devices (e.g., rotating drums, Dichgans & Brandt, 1973; moving rooms, Lishman & Lee, 1973), vehicle simulators (e.g., Kennedy, Lane, Lilienthal, Berbaum, & Hettinger, 1992; Stoffregen, Hettinger, Haas, Roe, & Smart, 2000), head-mounted displays (Draper, Viirre, Gawron, & Furness, 2001;

Address correspondence to Thomas A. Stoffregen, School of Kinesiology, Cooke Hall, 1900 University Ave. SE, Minneapolis, MN 55455; tas@umn.edu.

Merhi, Faugloire, Flanagan, & Stoffregen, 2007), and video games (Stoffregen, Faugloire, Yoshida, Flanagan, & Merhi, 2008 [this issue]).

Many questions about motion sickness remain. One question concerns the extent to which phenomena relating to motion sickness are general across different situations. This issue addresses the ability to predict motion sickness susceptibility across situations. It would be useful if one could use a person's susceptibility to motion sickness in a laboratory device to predict his or her susceptibility to motion sickness in an operational system, such as flight. Similarly, it would be convenient to use a person's susceptibility to motion sickness while playing video games, for example, to predict their risk of motion sickness while piloting high-performance aircraft.

Existing schemes for predicting motion sickness susceptibility across situations have had limited success. For example, motion sickness history (e.g., a person's previous experience of motion sickness in various settings) typically accounts for less than 35% of the variance in motion sickness incidence across situations (e.g., Kennedy, Dunlap, & Fowlkes, 1990). Thus, it is useful to assess the tendency of different situations to induce motion sickness.

Postural Instability Precedes Motion Sickness

Visually induced motion sickness is preceded by changes in postural activity that are limited to persons who will later become motion sick. Postural instability has preceded motion sickness in studies using widely differing types of visual motion, including linear oscillations along the line of sight (e.g., Bonnet, Faugloire, Riley, Bardy, & Stoffregen, 2006; Stoffregen & Smart, 1998), angular oscillations around the line of sight (Stoffregen et al., 2000), and multiaxis motions that occur in console video games (Stoffregen et al., 2008 [this issue]). This effect confirms a prediction of the postural instability theory of motion sickness (Riccio & Stoffregen, 1991).

Real and Virtual Moving Rooms

It can be difficult to assess the relative incidence of motion sickness across display technologies, mainly because the stimulus motions used typically differ across display technologies. Moving rooms oscillate linearly, flight simulators oscillate in angular motion, video games move in ways that are not under experimental control, and so on. The assessment of motion sickness falls within the larger category of efforts to assess the human factors characteristics of different display technologies. Many studies have compared real and virtual environments, but most comparisons have focused on presence or on task performance (Lathan, Tracey, Sebrechts, Clawson, & Higgins, 2002). Our comparison is unusual in that we collected quantitative data on perceptually guided movement (postural control) in the context of motion sickness.

We sought to determine whether phenomena observed with one display technology would occur when similar motion stimuli were presented via a different display technology. In previous research, we have investigated relations between motion sickness and postural activity in a moving room. In the present study, we used a projection video system. Projection video systems are used in a wide variety of applications, many of which are not related to motion sickness. For example, video projection systems are commonly used in

laboratory research relating the control of upright posture to parameters of optic flow (e.g., Warren, Kay, & Yilmaz, 1996).

Direct comparisons of postural responses to different optical display technologies are rare. Stoffregen, Bardy, Merhi, & Oullier (2004) found that postural responses to a moving room differed significantly from postural responses to a video projection system. Standing participants viewed optic flow displays of equal visual angle and visual pattern, and with equal motion amplitude and frequency. One display was created by the physical displacement of an illuminated surface, and the other was created using computer graphics and a video projector. Coupling of body sway with imposed optic flow was immediate when participants were exposed to a moving room. When they were exposed to a graphic simulation, coupling was not present initially but developed over time during exposure.

If postural responses differ in real and virtual moving rooms, then motion sickness (and related changes in postural activity) might also differ. This issue provides a motivation for the use of a video projection system in the present study. We tested two hypotheses: (a) that a virtual moving room would elicit motion sickness and (b) that prior to the onset of subjective symptoms of motion sickness, movement would differ between participants who eventually became motion sick and those who did not.

METHOD

To assess effects of the display technology, it is important to equate, as much as possible, the “contents” of visual stimuli presented via different display technologies. Toward this end, we developed a “virtual moving room.” We found that the spatiotemporal resolution and contrast of the video projection system were insufficient to permit reproduction of the amplitude of room oscillations (and, consequently, of the visual angle of optic oscillations). Room motion has been of small amplitude (1.8 cm in most experiments), and the pattern on the walls of the room is of low contrast (Figure 1, left panel). To ensure that the display motion was clearly visible, we “papered” the virtual moving room with a bold, high-contrast floral pattern (Figure 1, right panel). We also increased the amplitude of simulated motion to avoid pixilation (aliasing) and to ensure that the motion would be visible. We retained the sum-of-sines motion function that we have used in the moving room.

Participants

Twelve undergraduate students from the University of Minnesota participated after giving informed consent. There were 3 men and 9 women, ranging in age from 20 to 22 years, in weight from 54.43 to 111.58 kg (mean = 67.81 kg), and in height from 157.48 to 185.42 cm (mean = 168.48 cm). All participants stated that they were in good health and that they had no history of dizziness, falls, or inner ear disorders, and the women stated that they were not pregnant. Each participant demonstrated that he or she could stand on one leg with eyes open for 30 s. The Institutional Review Board of the University of Minnesota approved the protocol.

Apparatus and Stimulus

The stimulus consisted of a QuickTime movie showing a simulated room that oscillated along the viewers' line of sight (Figure 1, right panel). The central wall in the simulation varied in horizontal visual angle from 42° to 53°, corresponding to nominal simulated peak-to-peak oscillation amplitude of 22 cm.

The QuickTime file was run on an Apple G5 computer, and the imagery was presented using a video projector (DP9250+, Proxima Corp., San Diego, CA) with 60-Hz frame rate and 800 × 600 pixels, rear-projected onto a translucent screen 2.30 m wide and 1.30 m high. The projector was mounted on the ceiling, with the projection lens 2.10 m above the floor and 3.75 m from the screen. The vertical center of the screen was 1.4 m above the floor. Black cloth mounted on the screen occluded the edges of the projected image. The experimental area was curtained off using floor-to-ceiling black cloth on each side; overall room lights were dimmed. Movement of the head and torso was monitored using a magnetic tracking system (Fastrak, Polhemus, Inc., Colchester, VT).

Procedure

Participants were run individually. After the participants received an explanation of the study and indicated approval by signing the consent form, they filled out the Simulator Sickness Questionnaire, or SSQ (Kennedy, Lane, Berbaum, & Lilienthal, 1993). They were asked to discontinue immediately if they felt any symptoms of motion sickness, however slight. Participants stood with their heels on a line that was 1.25 m from the screen. Participants wore foam earplugs to dampen ambient sound. For safety reasons they also wore a bicycle helmet, which also served as base for a sensor from the magnetic tracking system. One sensor was attached to the helmet with Velcro, and another sensor was attached to the skin between the shoulder blades with cloth medical tape. Each sensor was sampled at 60 Hz.

For each trial, participants were asked to stand comfortably, with their heels on the line and their arms at their sides. They were asked not to move their feet during trials. In Trial 1, we recorded 60 s of spontaneous postural activity with the participant's eyes open. In Trial 1, the visual stimulus consisted of a stationary image of the room. In Trial 2, we recorded 60 s of spontaneous postural activity with the participant's eyes closed.

For Trials 3 through 6, the QuickTime movie was shown. The movie depicted oscillation of the virtual moving room. The oscillation function was the sum of 10 sine waves, with frequencies of 0.0167, 0.0416, 0.0783, 0.1050, 0.1670, 0.1800, 0.1900, 0.2200, 0.2600, and 0.3100 Hz. Using a magnetic tracking system, we recorded position data from the physical moving room as it oscillated with this sum of sines. The raw file of these position data was used to generate the oscillation function of the virtual moving room. The movie was 600 s in duration. The same movie was used in Trials 3, 4, 5, and 6. Rest breaks of up to 120 s were given between the 10-min trials (Trials 3–6).

The experimental session was terminated immediately when a participant reported any symptoms of motion sickness. After the end of participation (either through discontinuation or after the completion of all trials), participants were asked to indicate, on a yes/no basis,

whether they were motion sick. Participants who stated that they were motion sick were asked to fill out the postexposure SSQ immediately. Participants who stated that they were not motion sick were asked to report on their motion sickness status over the next 24 hr. They were also given a printed copy of the SSQ, which they were asked to fill out at the time of symptom onset or after 24 hr if no symptoms developed.

Analysis of Movement Data

The independent variables in our analyses were group (sick vs. well) and axis (anteroposterior and mediolateral). In Trials 1 and 2, we analyzed vision (eyes open vs. closed). In the sum-of-sines trials, we analyzed exposure duration (window), which is described later.

We separately analyzed movement of the head and torso. Position data were used to compute the path length – that is, the total linear displacement. Variability of position was also computed in the anteroposterior (AP) and mediolateral (ML) axes. Position data were differentiated to yield movement velocity in AP and ML.

Finally, we conducted detrended fluctuation analysis (DFA) on the time series of position. DFA describes the relation between the magnitude of fluctuations in postural motion and the time scale over which those fluctuations are measured (Chen, Ivanov, Hu, & Stanley, 2002). DFA has been used in several studies of unperturbed stance (e.g., Riley, Balasubramaniam, & Turvey, 1999), as well as in previous work relating postural activity to visually induced motion sickness (e.g., Bonnet et al., 2006). We conducted inferential tests on α, the scaling exponent of DFA. The scaling exponent is an index of long-range autocorrelation in the data – that is, the extent to which the data are self-similar over time. White noise, which is uncorrelated, yields $\alpha = .5$. The presence of long-range autocorrelation is indicated by $\alpha > .5$.

For each significant effect in our ANOVAs, we estimated the effect size using the η^2 statistic, which is the ratio of the between-groups sum of squares divided by the total sum of squares (Darlington & Carlson, 1987). The η^2 statistic describes the percentage of total variance that is accounted for by the effect under consideration.

RESULTS

Motion Sickness Incidence and Severity

Five participants (all women) stated that they were motion sick (42%), and they constituted the sick group. Of these, 3 participants discontinued during Trial 4 (i.e., the second sum-of-sines trial), at 4 min 56 s, 5 min 56 s, and 6 min 27 s after the beginning of the trial. The remaining 2 sick participants discontinued during Trial 5. One participant discontinued 48 s after the beginning of Trial 5, and the other discontinued after 2 min 29 s. The remaining 7 participants (3 men and 4 women) stated that they were not motion sick, and they constituted the well group. Each member of the well group completed the experiment.

Data on symptom severity are summarized in Figure 2. Scores on the SSQ are not normally distributed (e.g., Kennedy et al., 1993), so we evaluated these data using nonparametric

statistics. We used the Mann-Whitney *U* test to compare the rank of scores between the sick and well groups, and the Wilcoxon signed rank test to compare the rank of pretest and posttest scores within each group. We used the exact *p* value for each test and set the criterion alpha level at .025 (two-tailed) because the SSQ data were used in two separate tests.

At pretest, scores for the well and sick groups did not differ, $U = 15$, $p > .025$. At posttest, scores for the sick group (mean rank = 103.2) were higher than those for the well group (mean rank = 4.3), $U = 0$, $p < .025$. For the well group, the pretest scores (mean rank = 10.3) did not differ from the posttest scores (mean rank = 4.3), $z = -2.02$, $p > .025$. For the sick group, posttest scores (mean rank = 103.2) were significantly higher than pretest scores (mean rank = 5.2), $z = -2.26$, $p < .025$.

Movement Data

Spontaneous sway (Trials 1 and 2)—The data are summarized in Table 1. We conducted separate 2 (group: sick vs. well) × 2 (vision: eyes open vs. closed) × 2 (axis: AP vs. ML) ANOVAs on position, velocity, and α for the head and torso. For path length, we conducted a two-factor ANOVA on group and vision. Here we report only those significant effects that involved the group variable (main effects of vision are noted in Table 1).

We found significant Group × Axis interactions for the variability of head position, $F(1, 10) = 6.18$, $p < .05$, $\eta^2 = 2\%$, and for the velocity of head movements, $F(1, 10) = 8.42$, $p < .05$, $\eta^2 = 1\%$. In the variability data, the difference between AP and ML movements was greater for the well group than for the sick group (Figure 3, left panel). In the velocity data, the difference between AP and ML was greater for the sick group than for the well group (Figure 3, right panel).

DFA revealed significant Group × Vision × Axis interactions for head movements, $F(1, 10) = 45.78$, $p < .001$, $\eta^2 = 2\%$, and torso movements, $F(1, 10) = 29.38$, $p < .001$, $\eta^2 < 1\%$. As illustrated in Figure 4, the difference between the AP and ML axes was opposite for the well and sick groups when their eyes were open (Trial 1), whereas this difference was in the same direction when the eyes were closed (Trial 2).

Sum-of-sines trials: Evolution of sway over time—We sought to equate, as nearly as possible, the duration of exposure of the sick and well participants. To do this, we chose the median number of completed trials for the sick group as the number of trials to include in our analysis. Three of the sick participants discontinued after Trial 3 (i.e., the first sum-of-sines trial), whereas the other 2 sick participants completed Trial 4. Accordingly, we included in our analysis only the first sum-of-sines trial (Trial 3).

We evaluated the evolution of sway over the duration of Trial 3. To do this, we selected three windows from the data, each of which was 2 min in duration. Following Bonnet et al. (2006) and Faugloire, Bonnet, Riley, Bardy, and Stoffregen (2007) we selected three time windows from the data at the beginning, the middle, and the end of Trial 3. The first window comprised the first 120 s of the trial, the second window comprised the central 120 s (the 5th and 6th min of the trial), and the third window comprised the final 120 s (the 9th and 10th

min). For each dependent variable we conducted separate two-factor ANOVAs for Group (sick vs. well) × Window (first, middle, last), with repeated measures on the second factor. Again, we report only those significant effects that included the group factor. Representative raw data for torso movement are presented in Figure 5.

As illustrated in Figure 6, we found significant Group × Windows interactions for the path length of head movements, $F(2, 20) = 4.16$, $p < .05$, $\eta^2 = 1\%$, and torso movements, $F(2, 20) = 4.42$, $p < .05$, $\eta^2 = 4\%$. The Group × Window interaction was significant also for the velocity of torso movements, $F(2, 20) = 4.48$, $p < .05$, $\eta^2 = 1\%$. In each of these interactions, the increase in movement across windows was greater for the sick group than for the well group.

The Group × Axis interaction was significant for the velocity of torso movements, $F(1, 10) = 7.29$, $p < .05$, $\eta^2 = 2\%$. Figure 7 shows that the difference between ML and AP was greater for the sick group than for the well group.

Finally, for movement of the torso, DFA revealed a significant Group × Window × Axis interaction for α, $F(2, 20) = 4.11$, $p < .05$, $\eta^2 < 1\%$ (Figure 8). In the AP axis, sick/well differences were consistent over time (Figure 8, right panel), whereas in the ML axis differences between sick and well participants tended to increase over time (Figure 8, left panel). Using a physical moving room, Bonnet et al. (2006) found a main effect of group for α in the ML axis when participants were exposed to a simple 0.2-Hz motion for 120 s, but not during the sum-of-sines trials.

DISCUSSION

The incidence and severity of motion sickness in our study did not differ from that found in the physical moving room (Bonnet et al., 2006; Stoffregen & Smart, 1998), confirming that the two display systems were similarly nauseogenic. The effects relating head and torso motion to subsequent motion sickness were qualitatively similar to effects observed in previous studies using a physical moving room.

Motion Sickness

The incidence of motion sickness in the present study (42%) was essentially identical to that in the most nearly comparable study using a physical moving room (44%; Bonnet et al., 2006). The severity of symptoms (among participants reporting motion sickness) also did not differ across studies. In sum, we found no evidence that the nauseogenic properties of the virtual moving room differed from those of the corresponding physical moving room, despite differences in the visual angle of the motion display, the magnitude of simulated motion, and so on. The principal factor that was preserved across the studies was the range of frequencies of stimulus motion, and the results support the hypothesis that visually induced motion sickness is strongly related to the frequencies of imposed motion (Guignard & McCauley, 1990).

Postural Activity Prior to Motion Sickness

Changes in postural activity preceded the subjective symptoms of motion sickness, confirming our prediction that motion sickness should be preceded by changes in postural movement. This prediction has been confirmed in several different environments involving imposed visual motion, including physical moving rooms (Bonnet et al., 2006; Stoffregen & Smart,1998), a fixed-base flight simulator (Stoffregen et al., 2000), head-mounted displays (Merhi et al., 2007), and console video games (Merhi et al., 2007; Stoffregen et al., 2008 [this issue]), as well as a virtual moving room. As in these previous studies, motion sickness was preceded by sick/well movement differences during exposure to experimental motion (Trial 3) but also before participants were exposed to any experimental motion (Trials 1 and 2). The latter effect is consistent with those observed in some previous studies (Faugloire et al., 2007; Smart, Stoffregen, & Bardy, 2002; Stoffregen et al., 2000; Stoffregen & Smart, 1998).

We observed differences prior to motion sickness onset between the sick and well groups in parameters that are related to the magnitude of movement (variability, velocity, and path length). In addition, motion sickness was preceded by changes in α, the scaling exponent of DFA. Thus, postural activity differed between the sick and well groups in measures based on movement magnitude but also in a measure of activity that is independent of movement magnitude. These effects have implications for the development of general concepts of stability and instability in human movement: More movement does not necessarily imply less stability (e.g., Riccio & Stoffregen, 1988).

Differences in movement between the sick and well groups during exposure to experimental motion primarily involved changes over time (i.e., across windows) – that is, Group × Window interactions. One exception was a significant Group × Axis interaction for the velocity of torso movement (Figure 7). Using a physical moving room, Bonnet et al. (2006) found that the velocity of sway tended to increase across windows, but they did not find any evidence that the movement of sick and well participants changed differentially over time during exposure. In the sum-of-sines trials, Bonnet et al. (2006) did not find effects on α in the sum-of-sines trials, but we did. As with our other measures of movement, effects were limited to interactions involving group and window.

To summarize, in the physical moving room (Bonnet et al., 2006) the sick and well groups differed from beginning to end of exposure to experimental motion, whereas in the present study the differences between sick and well participants increased with the duration of exposure. Earlier tests of the postural instability theory of motion sickness have found main effects of group on sway in a moving room (Smart et al., 2002) and in a flight simulator (Stoffregen et al., 2000). These studies did not examine sway as a function of exposure duration, and so they cannot be compared with the present study on this variable.

This difference between Bonnet et al. (2006) and the present study may relate to the fact that experimental motion was presented as a virtual rather than a physical moving room. Stoffregen et al. (2004) compared postural responses to physical and virtual moving rooms. They found that coupling of body sway with stimulus motion was delayed in a virtual moving room, relative to coupling that was observed in a physical moving room. All trials

were 60 s in duration. Stoffregen et al. (2004) examined coupling in the first 30 s and the last 30 s of trials. In the virtual moving room, coupling of body sway with the motion stimulus was significantly stronger in the second half of trials; this was not true in the physical moving room.

That study, together with the current results, suggests that research on the visual control of stance that relies on virtual simulations (e.g., Warren et al., 1996) may have limited generalizability to relations between vision and stance outside the laboratory. Despite researchers' best efforts, participants can easily distinguish even the best simulations from the corresponding real-world situations (e.g., Stanney, Mourant, & Kennedy, 1998). Coupling of postural control with a graphics animation may require a level of deliberate choice that does not appear to be required in a moving room (Stoffregen, Bardy, Smart, & Pagulayan, 2003).

The present study suggests that postural activity (prior to motion sickness onset) may predict motion sickness incidence. Similar conclusions have been reached by Smart et al. (2002) and Smart, Otten, and Stoffregen (2007), who modeled postural data from several different venues, including a physical moving room, a flight simulator, and a head-mounted display. In both of those studies, motion sickness across experiments and venues was predicted by variability of head position, accounting for up to 60% of the variance and correctly classifying up to 70% of individual participants as being either sick or well. Taken together, the three studies suggest that changes in postural activity not only precede motion sickness but also can be used to predict it.

CONCLUSION

The video projection system induced motion sickness, with incidence and severity very similar to what has been observed in the corresponding physical moving room. Motion sickness was preceded by changes in body sway. Differences in movement between the sick and well groups were observed to develop over time during exposure to visual stimulus motion, rather than being present throughout exposure, as has been observed in the physical moving room (Bonnet et al., 2006; Stoffregen et al., 2004). We conclude that whereas the contents of the display (i.e., visual oscillation along the line of sight) were important for visually induced motion sickness, the technology of the display was also important.

Acknowledgments

This research was supported by the National Institute on Deafness and Other Communication Disorders (R01 DC005387-01A2) and by the University of Minnesota Games Research and Virtual Environment Laboratory.

REFERENCES

Bonnet CT, Faugloire E, Riley MA, Bardy BG, Stoffregen TA. Motion sickness preceded by unstable displacements of the center of pressure. Human Movement Science. 2006; 25:800–820. [PubMed: 16707179]

Chen Z, Ivanov PC, Hu K, Stanley HE. Effect of non-stationarities on detrended fluctuation analysis. Physical Review E. 2002; 65:041107-1–041107-14.

Darlington, RB.; Carlson, PM. Behavioral statistics. New York: Free Press; 1987.

Dichgans J, Brandt T. Optokinetic motion sickness and pseudo-Coriolis effects induced by moving visual stimuli. Acta Otolaryngologica. 1973; 76:339–348.

Draper MH, Viirre ES, Gawron VJ, Furness TA. The effects of virtual image scale and system delay on simulator sickness within head-coupled virtual environments. Human Factors. 2001; 43:129–146. [PubMed: 11474759]

Faugloire E, Bonnet CT, Riley MA, Bardy BG, Stoffregen TA. Motion sickness, body movement, and claustrophobia during passive restraint. Experimental Brain Research. 2007; 177:520–532. [PubMed: 17021895]

Guignard, JC.; McCauley, ME. The accelerative stimulus for motion sickness. In: Crampton, GH., editor. Motion and space sickness. Boca Raton, FL: CRC Press; 1990. p. 123-152.

Kennedy, RS.; Dunlap, WP.; Fowlkes, JE. Prediction of motion sickness susceptibility. In: Crampton, GH., editor. Motion and space sickness. Boca Raton, FL: CRC Press; 1990. p. 179-216.

Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG. Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. International Journal of Aviation Psychology. 1993; 3:203–220.

Kennedy RS, Lane NE, Lilienthal MG, Berbaum KE, Hettinger LJ. Profile analysis of simulator sickness symptoms: Application to virtual environment systems. Presence. 1992; 1:295–301.

Lathan, CE.; Tracey, MR.; Sebrechts, MM.; Clawson, DM.; Higgins, GA. Using virtual environments as training simulators: Measuring transfer. In: Stanney, K., editor. Handbook of virtual environments: Design, implementation, and applications. Mahwah, NJ: Erlbaum; 2002. p. 403-414.

Lishman JR, Lee DN. The autonomy of visual kinaes-thesis. Perception. 1973; 2:287–294. [PubMed: 4546578]

Merhi O, Faugloire E, Flanagan M, Stoffregen TA. Motion sickness, console video games, and head-mounted displays. Human Factors. 2007; 49:920–934. [PubMed: 17915607]

Riccio GE, Stoffregen TA. Affordances as constraints on the control of stance. Human Movement Science. 1988; 7:265–300.

Riccio GE, Stoffregen TA. An ecological theory of motion sickness and postural instability. Ecological Psychology. 1991; 3:195–240.

Riley MA, Balasubramaniam R, Turvey MT. Recurrence quantification analysis of postural fluctuations. Gait and Posture. 1999; 9:65–78. [PubMed: 10575072]

Smart, LJ.; Otten, EW.; Stoffregen, TA. It's turtles all the way down: A comparative analysis of visually induced motion sickness. Proceedings of the Human Factors and Ergonomics Society 51st Annual Meeting; Human Factors and Ergonomics Society; Santa Monica, CA. 2007. p. 1631-1634.

Smart LJ, Stoffregen TA, Bardy BG. Visually induced motion sickness predicted by postural instability. Human Factors. 2002; 44:451–465. [PubMed: 12502162]

Stanney KM, Mourant RR, Kennedy RS. Human factors issues in virtual environments: A review of the literature. Presence. 1998; 7:327–351.

Stoffregen TA, Bardy BG, Merhi O, Oullier O. Postural responses to two technologies for generating optical flow. Presence. 2004; 13:601–615.

Stoffregen, TA.; Bardy, BG.; Smart, LJ.; Pagulayan, RJ. On the nature and evaluation of fidelity in virtual environments. In: Hettinger, LJ.; Haas, MW., editors. Virtual and adaptive environments: Applications, implications, and human performance issues. Mahwah, NJ: Erlbaum; 2003. p. 111-128.

Stoffregen TA, Faugloire E, Yoshida K, Flanagan MB, Merhi O. Motion sickness and postural sway in console video games. Human Factors. 2008; 50:322–331. (this issue). [PubMed: 18516842]

Stoffregen TA, Hettinger LJ, Haas MW, Roe M, Smart LJ. Postural instability and motion sickness in a fixed-base flight simulator. Human Factors. 2000; 42:458–469. [PubMed: 11132807]

Stoffregen TA, Smart LJ. Postural instability precedes motion sickness. Brain Research Bulletin. 1998; 47:437–448. [PubMed: 10052572]

Warren WH, Kay BA, Yilmaz EH. Visual control of posture during walking: Functional specificity. Journal of Experimental Psychology: Human Perception and Performance. 1996; 22:818–838. [PubMed: 8756954]

Biographies

Sébastien J. Villard is a postdoctoral fellow in the School of Kinesiology at the University of Minnesota. He received his Ph.D. in human movement sciences from the University of Montpellier-1, France, in 2005.

Moira B. Flanagan is a postdoctoral associate in the School of Kinesiology, University of Minnesota. She received her Ph.D. in psychology at the University of New Orleans in 2005.

Gina M. Albanese is a graduate student in the Center for Cognitive Sciences at the University of Minnesota. She received her M. Arch. in architecture from Princeton University in 2005.

Thomas A. Stoffregen is a professor of kinesiology at the University of Minnesota. He received his Ph.D. in psychology from Cornell University in 1984.

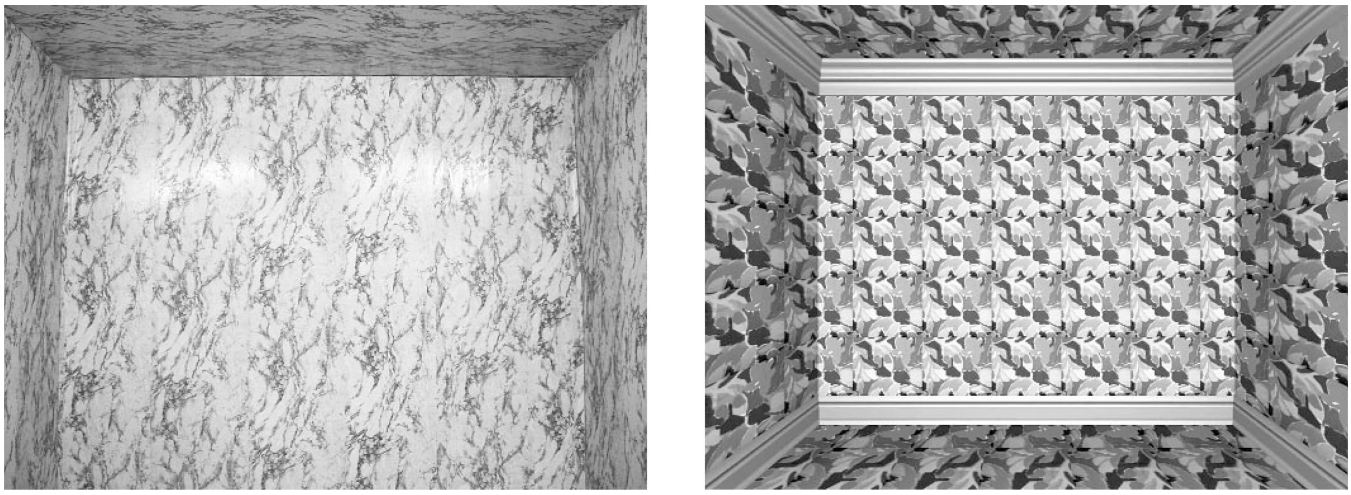

Figure 1.
A photograph of the physical moving room (left panel), and a frame from the virtual moving room (right panel).

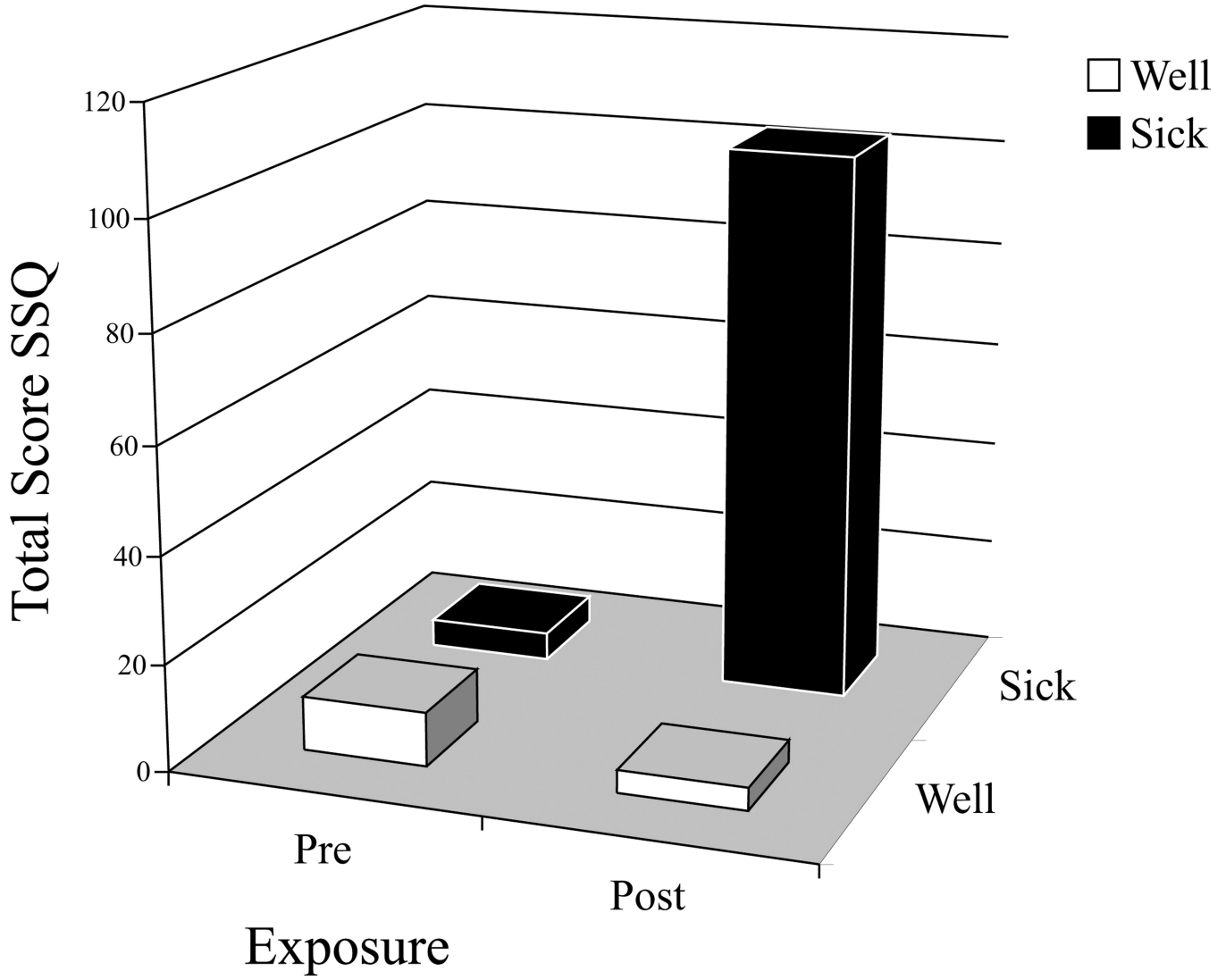

Figure 2.
Simulator Sickness Questionnaire (SSQ) total severity scores before (pre) and after (post) exposure to the virtual moving room for the well and the sick groups.

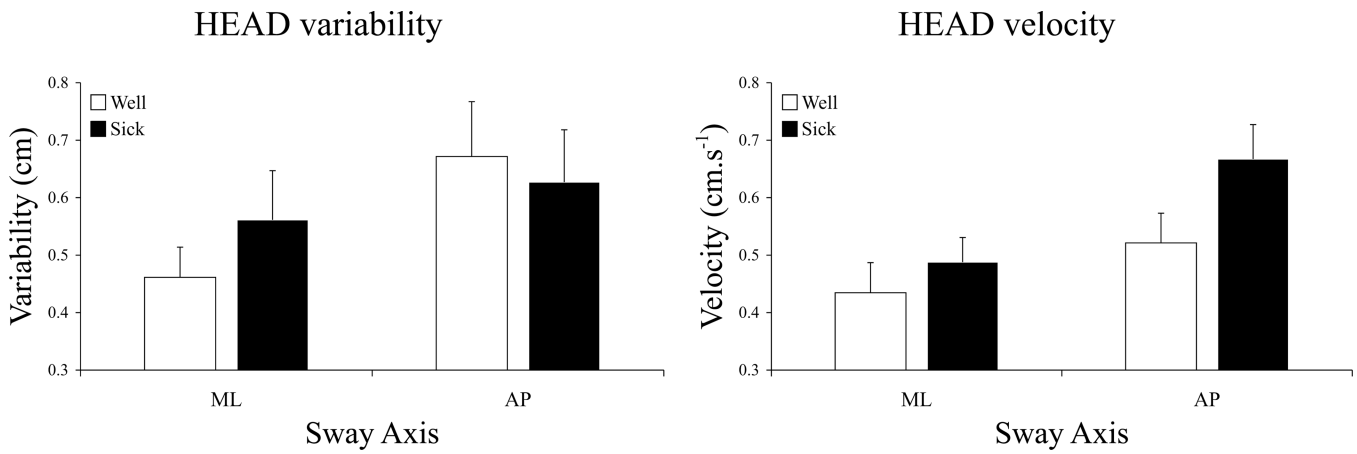

Figure 3.

Movement during unperturbed stance (Trials 1 and 2). The figure illustrates Group (sick vs. well) × Axis (AP vs. ML) interactions for the variability (left panel) and velocity (right panel) of the head movements. The error bars represent standard error. ML = mediolateral, AP = anteroposterior.

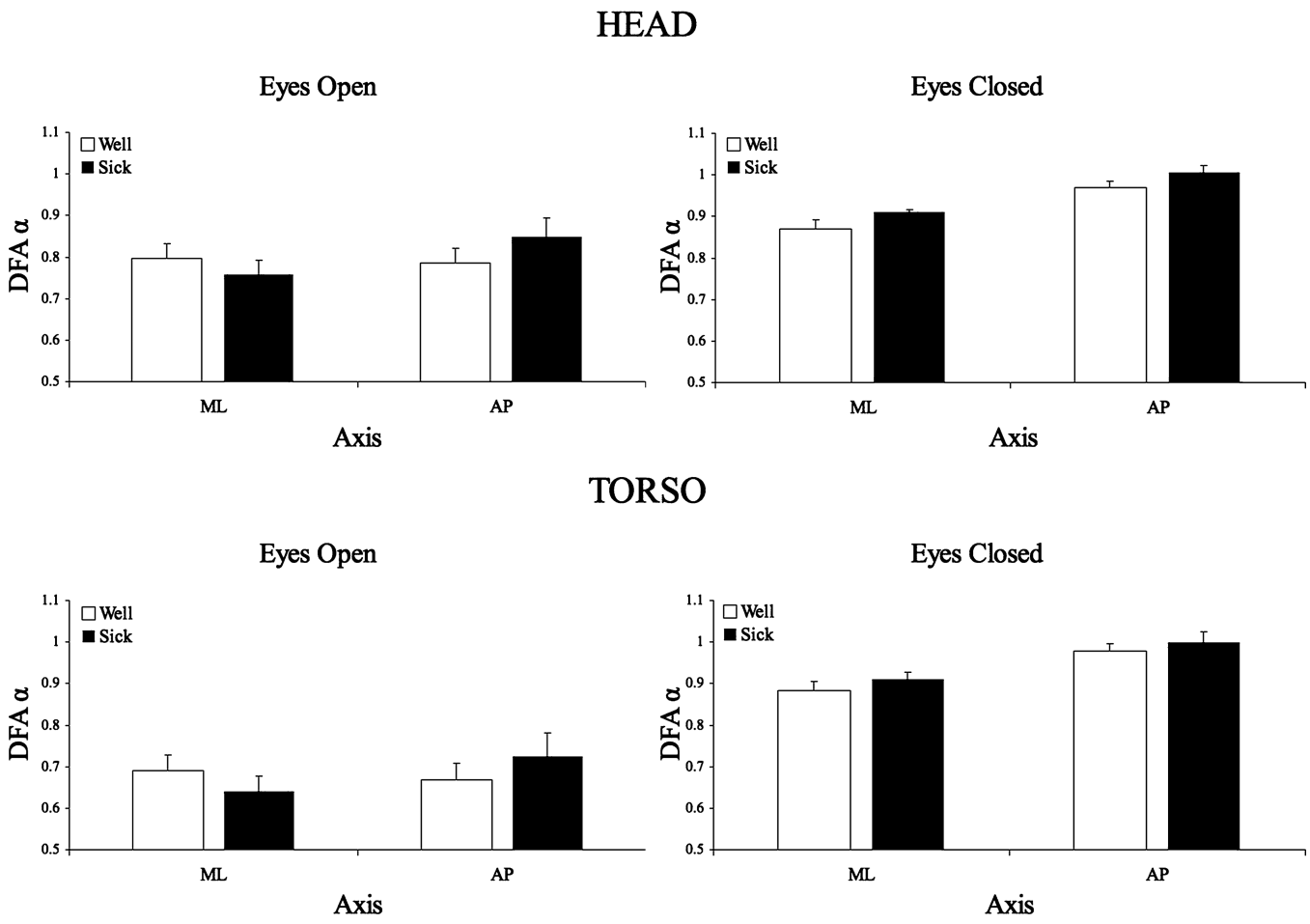

Figure 4.

Movement during unperturbed stance (Trials 1 and 2), showing results of detrended fluctuation analysis. The figure illustrates Group × Vision × Axis interactions on the scaling exponent, α, for head movements (top panels) and torso movements (bottom panels). The error bars represent standard error. ML = mediolateral, AP = anteroposterior.

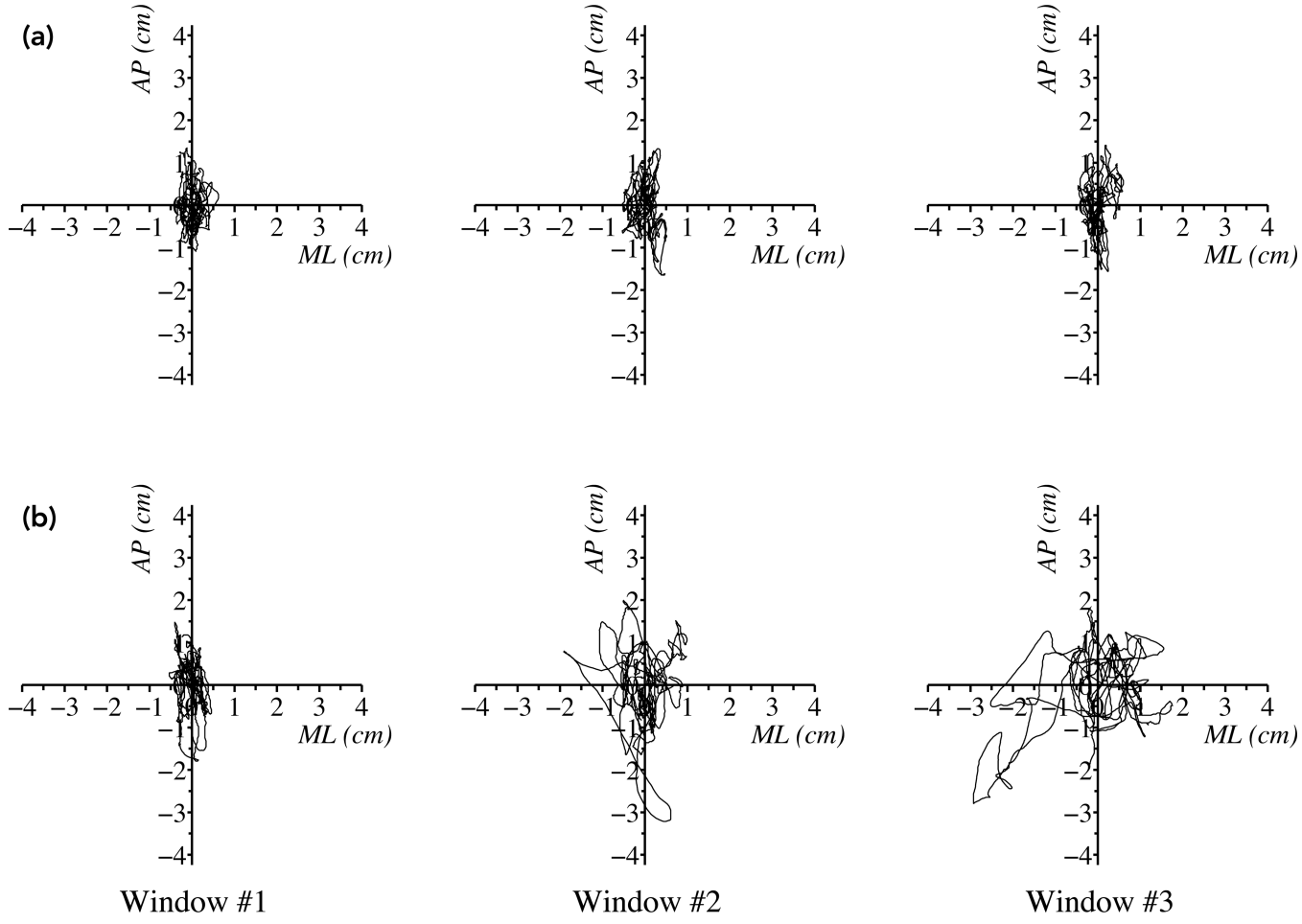

Figure 5.

Representative data for torso movement during the three windows selected from Trial 3. (a) A participant from the well group. (b) A participant from the sick group. ML = mediolateral, AP = anteroposterior.

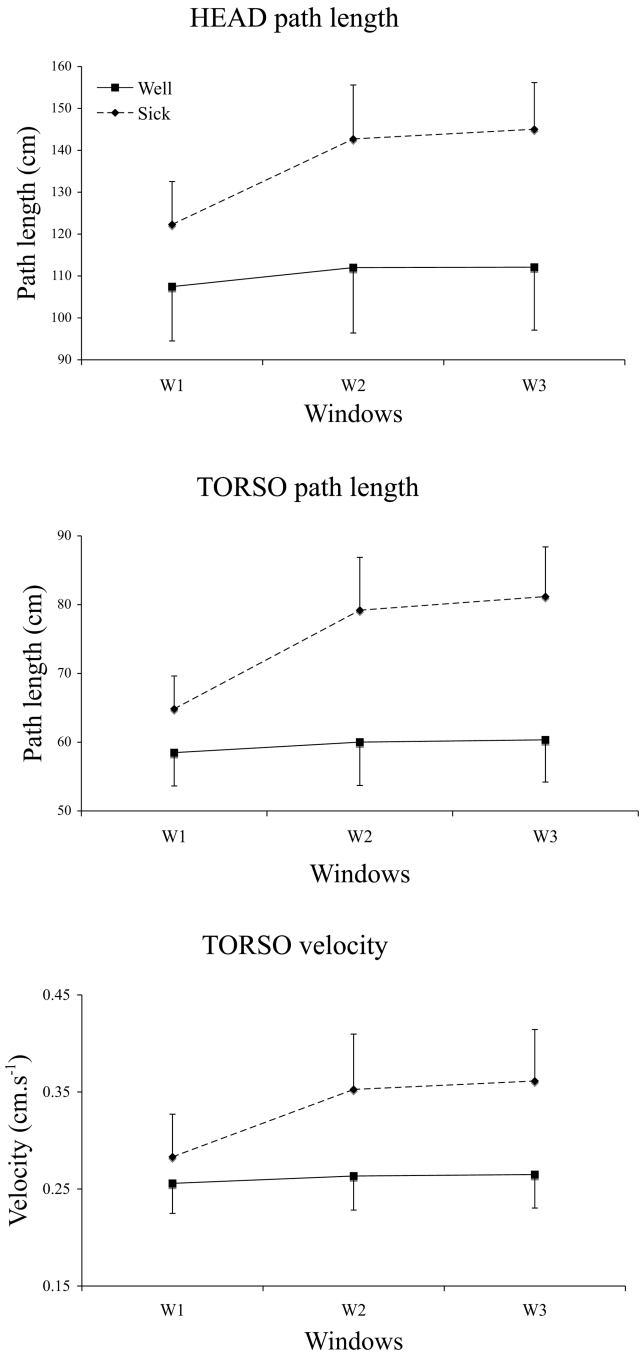

Figure 6.

Movement data during exposure to the sum-of-sines stimulus (Trial 3), illustrating Group × Windows interactions for the path length of movements of the head (top panel) and torso (middle panel) and for the velocity of torso movements (bottom panel). The error bars represent standard error. W1, W2, and W3 = Windows 1, 2, and 3.

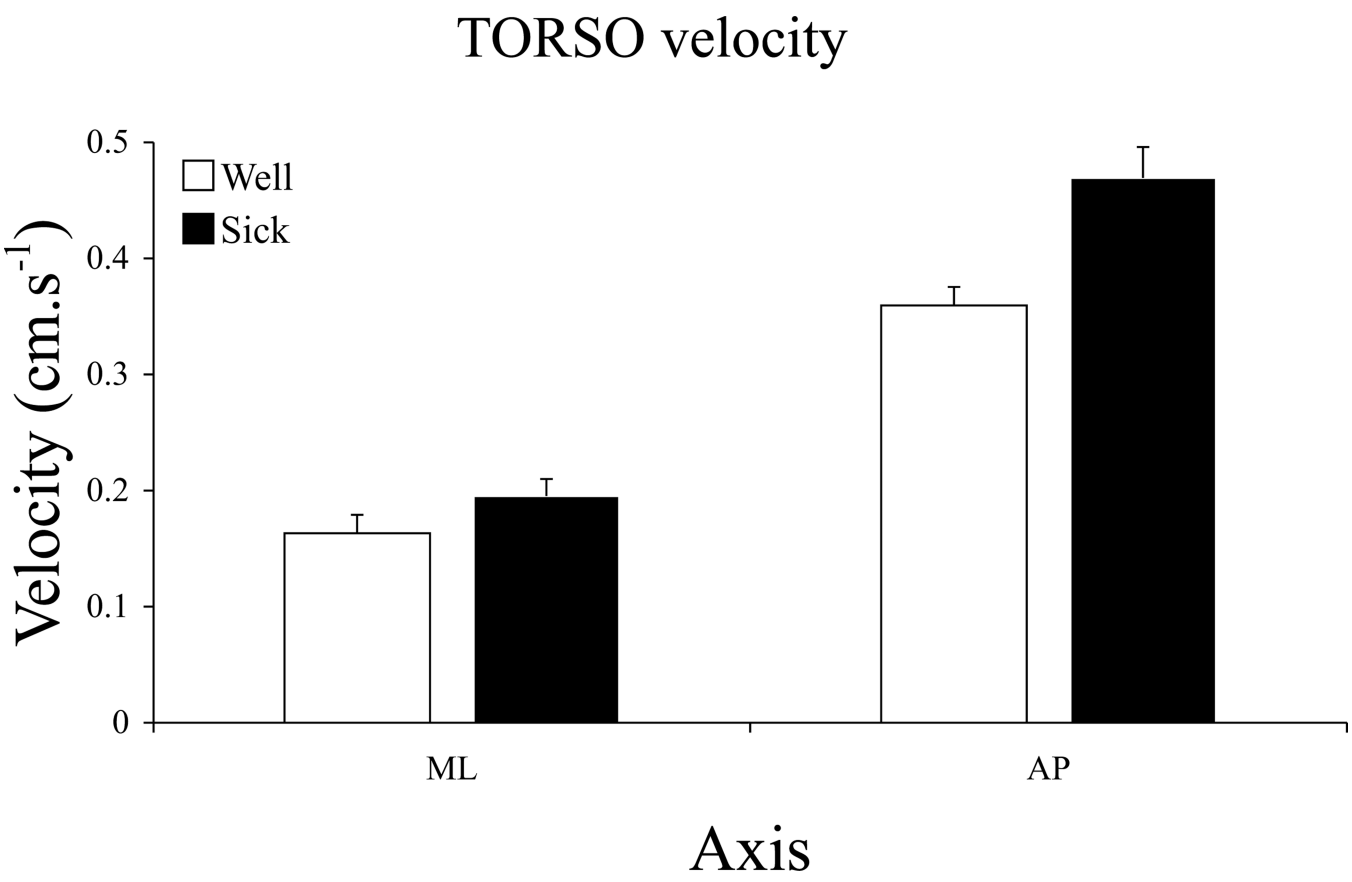

Figure 7.
Movement data during exposure to the sum-of-sines stimulus (Trial 3), illustrating the Group × Axis interaction for the velocity of torso movements. The error bars represent standard error. ML = mediolateral, AP = anteroposterior.

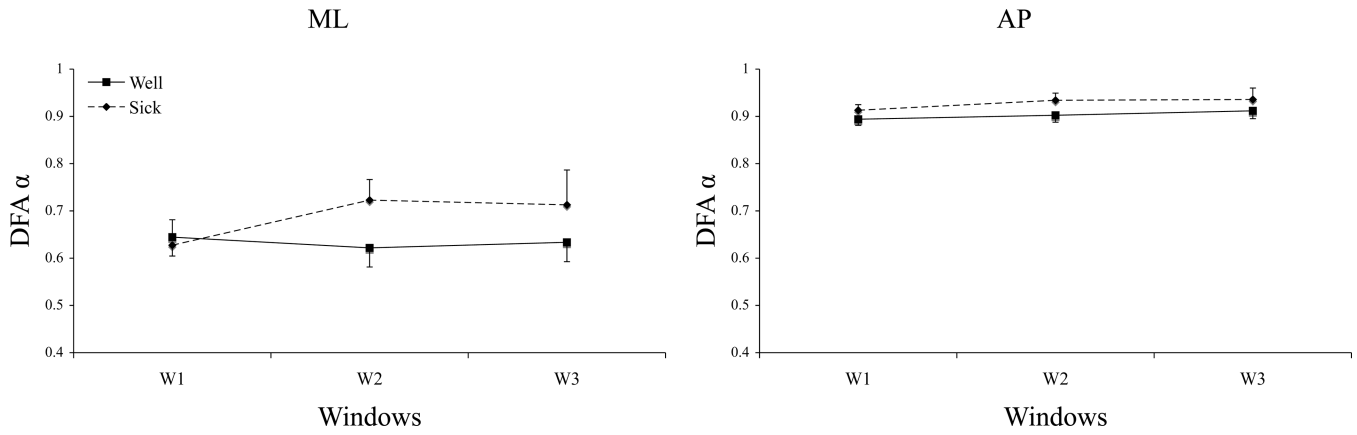

Figure 8.

Movement of the torso during exposure to the sum-of-sines stimulus (Trial 3), showing results of detrended fluctuation analysis. The figure illustrates the Group × Window × Axis interaction on α, the scaling exponent of DFA. The error bars represent standard error. W1, W2, and W3 = Windows 1, 2, and 3; ML = mediolateral, AP = anteroposterior.

TABLE 1

Descriptive Statistics for Movement During Trials 1 and 2 (Spontaneous Sway)

		Eyes Open (Trial 1)		Eyes Closed (Trial 2)	
		ML	**AP**	**ML**	**AP**
Path length (cm)	Head*	51.12 (17.45)		62.87 (14.55)	
	Torso*	25.40 (5.94)		34.48 (5.82)	
Variability (cm)	Head*	0.44 (0.26)	0.45 (0.23)	0.56 (0.19)	0.85 (0.28)
	Torso*	0.18 (0.09)	0.20 (0.12)	0.40 (0.15)	0.58 (0.17)
Velocity (cm/s)	Head	0.46 (0.23)	0.51 (0.22)	0.45 (0.10)	0.65 (0.17)
	Torso*	0.15 (0.05)	0.17 (0.05)	0.28 (0.06)	0.42 (0.09)
DFA α	Head*	0.78 (0.09)	0.81 (0.10)	0.89 (0.05)	0.98 (0.04)
	Torso*	0.67 (0.09)	0.69 (0.11)	0.90 (0.05)	0.99 (0.05)

Note. AP = anteroposterior; ML = mediolateral; DFA = detrended fluctuation analysis.

* $p < .05$ for the main effect of vision (i.e., difference between Trial 1 and Trial 2).