Control of a Virtual Vehicle Influences Postural Activity and Motion Sickness

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Abstract

Everyday experience suggests that drivers are less susceptible to motion sickness than passengers. In the context of inertial motion (i.e., physical displacement), this effect has been confirmed in laboratory research using whole body motion devices. We asked whether a similar effect would occur in the context of simulated vehicles in a visual virtual environment. We used a yoked control design in which one member of each pair of participants played a driving video game (i.e., drove a virtual automobile). A recording of that performance was viewed (in a separate session) by the other member of the pair. Thus, the two members of each pair were exposed to identical visual motion stimuli but the risk of behavioral contagion was minimized. Participants who drove the virtual vehicle (drivers) were less likely to report motion sickness than participants who viewed game recordings (passengers). Data on head and torso movement revealed that drivers tended to move more than passengers, and that the movements of drivers were more predictable than the movements of passengers. Prior to the onset of subjective symptoms of motion sickness movement differed between participants who (later) reported motion sickness and those who did not, consistent with a prediction of the postural instability theory of motion sickness. The results confirm that control is an important factor in the etiology of motion sickness, and extend this finding to the control of non-inertial virtual vehicles.

keywords: motion sickness, posture, video games

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A common anecdotal report is that persons who are in control of a vehicle, such as drivers, are less likely to become motion sick than persons in the same vehicle who have no control over its motion (e.g., Geeze & Pierson, 1986; Howard & Templeton, 1966; Reason & Brand, 1975). In simple terms, drivers appear to be less likely than passengers to become motion sick. Research has confirmed that persons who control physical motion of laboratory devices are less susceptible to motion sickness than persons who are exposed to the same motion without being able to control it (Rolnick & Lubow, 1991). An equally important question concerns the control of simulated vehicles in virtual environments. We addressed this question using a new method that ensured that drivers and passengers were exposed to identical motion stimulation while minimizing the possibility of behavioral contagion. We also evaluated relations between postural activity and motion sickness in a virtual vehicle.

We focused on a virtual automobile in a console video game. There are many anecdotal reports of motion sickness among users of high fidelity, high-immersion console video game systems, such as Xbox, PlayStation, and Wii. These reports have been confirmed experimentally (Merhi, Faugloire, Flanagan, & Stoffregen, 2007; Stoffregen, Faugloire, Yoshida, Flanagan, & Merhi, 2008). If games were used solely for entertainment, such motion sickness might be considered to be relatively inconsequential. However, console video games are used in many non-entertainment settings. Contemporary video games require players to construct hypotheses, solve problems, develop strategies, and learn the rules of the in-game world through trial and error. Players must also be able to juggle several simultaneous tasks, evaluate risks and make quick decisions. In part for these reasons, computer games have been used for more than 25 years in performance testing of military personnel (e.g., Jones et al., 1981; Kennedy et al., 1982). Laboratory research with video games suggests that they may yield improvements in visuospatial memory in both game and non-game situations. Using standardized tests of perceptual load and useful field of view, Green and Bavelier (2006) showed that video game experience led to enhancement in attentional resources (in both peripheral and central vision), and to improvements in the distribution of visual attention (relative to subjects without game experience). This may explain why video games are widely used as educational tools for pilots, soldiers, and surgeons, as well as in schools and businesses. Hospitals in several states use video gaming in rehabilitation following stroke, spinal injuries, and other conditions, while the US Army uses video games to help injured soldiers recover their strength (Murph, 2007). In addition, the task demands of contemporary video games are related to many operational virtual reality systems. For example, training with virtual reality simulations improves the performance of surgeons (Ali et al., 2004; Rosser et al., 2007), while performance on video games predicts the quality of laparoscopic surgical performance (Rosenberg et al., 2005).

These factors suggest that video games may be a very useful form of preparation for the workplace of the 21st century. Unfortunately, the use of video games in education, research, and rehabilitation is threatened by reports of motion sickness among users. Hence, motion sickness research with video games can have implications for the design and use of game systems that extend beyond the entertainment industry, and for the design and use of simulator and virtual environment systems, in general. Such research can also have implications for general theories of the etiology of motion sickness.

Vehicular Control as an Etiological Factor in Motion Sickness

Reason and Brand (1975) argued that the differential susceptibility of drivers and passengers is important to a complete understanding of the etiology of motion sickness. Yet few experimental studies have investigated susceptibility to motion sickness as a function of whether a person was in control of a vehicle. Perhaps the main reason for the paucity of research has been methodological difficulties. A rigorous test of the role of vehicular control requires that some participants be able to control the motion while at the same time ensuring that all participants are exposed to identical motion stimuli. Few methodologies have met this criterion.

In the context of physical (i.e., inertial) motion, the most rigorous study of the role of vehicular control was reported by Rolnick and Lubow (1991). They used a purpose-built whole body motion device consisting of a platform that rotated around an earth-vertical axis. Two chairs were mounted on the platform. Rolnick and Lubow used a yoked control method, reminiscent of the "kitten carousel" of Held and Hein (1963), in which participants participated in pairs, with one person controlling the device and the other being exposed as a passenger. Several measures of motion sickness were lower for active participants than for their passive counterparts. An advantage of the yoked-control method is that we can be certain that motion of the rotating platform was identical for drivers and passengers. A disadvantage is the possibility of behavioral contagion between participants. Behavioral contagion occurs when one participant's risk of motion sickness is influenced by the sight, sound, or smell of another person being ill (e.g., Houchens & Jones, 2003).

Bodily Control as an Etiological Factor in Motion Sickness

Motion sickness situations are associated with changes in multisensory stimulation, a fact that figures prominently in the sensory conflict theory of motion sickness (e.g., Oman, 1982). It certainly is the case that multisensory stimulation on a ship or in a virtual environment (for example) differs from what we typically experience in daily life. However, sensory stimulation is not the only thing that differs between situations that are associated with motion sickness and those that are not. An additional factor that differs is constraints on control of bodily orientation. When we walk or run over the ground, we control our locomotion (i.e., speed and direction) relative to the ground while simultaneously maintaining our body balance relative to the ground. In vehicular travel the vehicle is controlled relative to the surroundings, but the body must be controlled (i.e., stablized) relative to the vehicle (e.g., Mayo, Wade, & Stoffregen, 2011). Control of the vehicle is limited to the driver or pilot, whereas control of the body is the responsibility of each individual, regardless of whether they are in control of the vehicle. Motion of the vehicle relative to the earth generates inertial forces that influence motion of bodies within the vehicle. Inertial motion (i.e., acceleration, whether linear, as occurs when speeding up or slowing down, or angular, as occurs in turns) alters the direction of balance, which is contraparallel to the vector sum of gravitational and inertial forces acting on the body (Stoffregen & Bardy, 2001). For this reason, vehicular travel alters the constraints on control of the body (e.g., Riccio, 1993). One visible manifestation of this fact is that people often lean during vehicle acceleration. This leaning is adaptive in the sense that it helps to maintain balance. Vehicle motion is often complex, with simultaneous changes in linear acceleration (i.e., speeding up and slowing down), and angular acceleration (i.e., turns). Because they control vehicle motion, drivers can anticipate changes in forces that influence stability of the body. For this reason, drivers' postural adjustments can be anticipatory in terms of the magnitude and axes of adjustments needed. Passengers have reduced ability to anticipate changes in vehicle motion and, as a result, passengers' postural adjustments will more often be compensatory, and will be less precisely tuned to situational changes in the magnitude and axes of vehicle motion. For this reason, passengers (as a group) will be at greater risk of instability in the control of body posture.

Unstable control of the body has been implicated as an etiological factor in motion sickness (Riccio & Stoffregen, 1991). Laboratory research has shown that subjective reports of motion sickness are preceded by changes in postural activity of body segments, such as the head and torso. Such effects have been found in the context of vehicle simulation (e.g., Stoffregen, Hettinger, Haas, Roe, & Smart, 2000), but also with simulations of non-vehicular locomotion (e.g., Merhi et al., 2007; Stoffregen et al., 2008) and with simulations of the visual consequences of standing body sway (e.g., Stoffregen & Smart, 1998; Villard, Flanagan, Albanese, & Stoffregen, 2008). Changes have been observed in the magnitude of movement, such as the range of body motion and the variability of body position (e.g., Stoffregen & Smart, 1998; Stoffregen et al.). Changes have also been observed in the temporal dynamics of movement, such as its predictability or self-similarity over time (e.g., Villard et al.). Movement magnitude and movement dynamics can differ qualitatively, and it is not yet clear which parameters of postural activity are specific to subsequent motion sickness. For this reason, there is both practical and theoretical value in evaluating both types of parameters. The occurrence of changes in postural activity, prior to any subjective feelings of motion sickness, among individuals who later report motion sickness confirms a prediction of the postural instability theory of motion sickness (Riccio & Stoffregen).

Physical Versus Virtual Vehicles

It is not obvious that motion sickness incidence in virtual vehicles will differ between drivers and passengers. Traditionally, motion sickness has been associated with inertial motion, that is, with physical displacement of the body. In recent decades motion sickness has become problematic in virtual vehicles. In virtual vehicles, inertial motion can be created using whole body motion devices, for example, by placing a cockpit atop a set of hydraulic jacks, as is done in many flight simulators. Non-inertial motion is created using visual and auditory displays. Many vehicle simulations include no inertial motion. In video games, millions of people engage in the control of virtual vehicles that are presented exclusively through vision and audition.

As noted above, the inertial character of motion in physical vehicles leads to adaptive adjustments in the control of body posture relative to the vehicle: Both drivers and passengers are obliged to control their posture relative to vehicle motion. Motion of virtual vehicles alters visual stimulation (optic flow) but does not alter the forces that constrain body balance. As a result, neither drivers nor passengers are required to control their posture relative to motion of a virtual vehicle. Leaning might occur in virtual vehicles (for example, leaning into turns may heighten the user's sense of immersion), but it would not be functionally related to alignment of the body relative to the direction of balance. Such leaning may actually be maladaptive in the sense that it would tend to move the body away from balance. In effect, leaning in a virtual vehicle would tend to destabilize rather than to stabilize posture. Virtual vehicles resemble physical vehicles in the sense that, in both, drivers have a greater opportunity than passengers to anticipate changes in vehicle motion. Yet virtual vehicles differ from physical vehicles in the sense that postural adjustments to motion of a virtual vehicle tend to reduce rather than to increase bodily stability. For this reason, it should not be assumed that differences in motion sickness incidence that have been observed between drivers and passengers in physical vehicles will also occur in virtual vehicles.

In laboratory research, motion sickness associated with console video games has been linked to persons who play the games; not to persons who watch as others play. We are not aware of any controlled research addressing motion sickness among people who watch video games that they do not control. In laboratory research, the incidence of motion sickness among players of console video games has ranged from 50% to 100% (Merhi et al, 2007; Stoffregen et al., 2008). Such high rates of motion sickness raise the possibility that control of action in non-vehicular console video games may not reduce the risk of motion sickness. In these same studies motion sickness among players of console video games has been preceded by changes in postural activity, consistent with the postural instability theory of motion sickness. These findings suggest that it may be useful to monitor postural activity while investigating the influence of vehicle control on motion sickness in virtual vehicles.

In the context of virtual environments, we know of only two experimental studies that have compared participants with and without control. In three conditions, Stanney and Hash (1998) varied the level of control that participants had over visual motion stimulation. In the passive condition, participants watched as an experimenter performed pre-scripted movements of the viewpoint within a virtual environment. In the active condition, participants controlled viewpoint motion in six degrees of freedom. In the active-passive condition, participants controlled fewer degrees of freedom. Motion sickness symptoms were more severe in the passive group than in the active or active-passive groups, consistent with the hypothesis that lack of control increased the risk of motion sickness. However, visual motion stimulation differed between conditions. Stanney and Hash acknowledged (p. 457) that visual motion differed between conditions. Thus, increased symptom severity in the passive condition might result from condition-related variations in visual motion, rather than from variations in user control. A similar problem applies to a study by Littman, Otten, and Smart (2010). Participants in the active condition played a video game, while participants in the passive condition watched as an experimenter played the game, such that active and passive participants were exposed to different visual motion stimuli. Finally, the virtual environments used by Stanney and Hash and Littman et al., did not include vehicles; locomotion consisted of walking, running, and jumping. Thus, neither study is directly relevant to relations between motion sickness and the control of virtual vehicles.

The Present Study

We developed a method in which participants with and without control of a virtual automobile were exposed to identical visual motion stimulation while minimizing the risk of behavioral contagion. Following Rolnick and Lubow (1991) we used a yoked-control design in which active and passive participants were paired. Individuals who controlled the game (drivers) were paired with individuals who watched game sessions (passengers). The game system that we used permitted game sessions to be recorded for later playback. This capability allowed us to expose drivers and passengers to identical visual motion in separate laboratory sessions. Only one participant was in the laboratory at any given time; thus minimizing the risk of behavioral contagion (Houchens & Jones, 2003).

We collected data on movement of the head and torso. We used these data for three purposes. First, we compared the overall magnitude of driver and passenger movements. We predicted that drivers would move more than passengers. Second, we evaluated a prediction of the postural instability theory of motion sickness etiology, which predicts that the subjective symptoms of motion sickness will be preceded by changes in movement of the body or its segments (Riccio & Stoffregen, 1991). In previous studies, motion sickness has been preceded by changes in movement of the head and/or torso when participants controlled visual motion stimuli (e.g., Merhi et al., 2007; Stoffregen et al., 2008) and when they viewed experimenter-controlled visual motion stimuli (e.g., Stoffregen & Smart, 1998; Villard et al., 2008), but active and passive participants have not been exposed to identical visual motion stimuli. We predicted that motion sickness would be preceded by changes in movement of the head and torso for both drivers and passengers.

Finally, we used movement data to evaluate the strength of coupling between drivers and passengers. Many studies have shown that imposed visual motion stimuli (i.e., optic flow) tend to influence movement of the body. Generally, body motion becomes coupled to oscillatory components of optic flow (e.g., Lee & Lishman, 1975; Oullier, Bardy, Stoffregen, & Bootsma, 2002). In the present study, the two members of each participant pair were exposed to the same game session (one as driver, one as passenger). If individuals coupled their movement to the dynamics of visual stimulus motion, then there would be (unintended) coupling between individuals (cf. Shockley, Santana, & Fowler, 2003). Unstable movement would tend to reduce an individual's coupling with events in the game, which in turn would tend to reduce coupling between participants. We predicted that the interpersonal coupling of movement would be lower when one member of a pair became motion sick than when neither member became sick.

Method

Participants

Twenty-six individuals (11 males and 15 females) participated. Their mean age was 23 years (SD = 7.6 years) and their mean height was 1.70 m (SD = 0.08 m). Participants were students at the University of Minnesota who participated in exchange for course credit, or on a voluntary basis. Each person participated in only one condition. The protocol was approved by the Institutional Review Board of the University of Minnesota.

Apparatus

Participants played *Forza Motosport 2*, a driving simulator game, on an Xbox 360 system. Each participant sat on a stool located in front of a plasma flat screen display (1.65 m diagonal). The absence of back support meant that participants were required to control the torso as well as the head. The stool was 1.8 m from the screen, yielding a visual angle of approximately 60° horizontal × 48° vertical (Merhi et al., 2007; Stoffregen et al., 2008). Participants were permitted to adjust the height of the stool to be comfortable, but were not permitted to move the stool toward or away from the screen. Stereo sound was presented through speakers built into the plasma display. Drivers played the game using a standard Xbox 360 controller, a handheld device with a joystick (operated by the left thumb). Positive acceleration (speeding up) was achieved with a button controlled using the left index finger, while negative acceleration (braking) was achieved via a button controlled using the right index finger. The right thumb operated two buttons that were used to shift gears; one button was used to shift to higher gear and the other shift to lower gear.

We used a magnetic tracking system (Fastrak, Polhemus, Inc., Colchester, VT) to collect movement data. One receiver was attached to a bicycle helmet (which weight 0.3 kg) and another to the skin at the level of the 7th cervical vertebra (i.e., between the shoulder blades), using cloth medical tape. The transmitter was located behind the participant's head, on a stand. Six-degree-of-freedom position data were collected from each receiver at 60 Hz and stored for later analysis.

Design and Procedure

Each driver drove a 2004 Audi R8 on the Suzuka circuit, which mimics an actual Formula One circuit of the same name. The course was a 5.8 km loop that included nine right turns and seven left turns. The course was flat, and paved. Among the courses available in *Forza Motosport 2*, the Suzuka circuit has been rated (MyCheats, 2010) as having a medium-high level of driving difficulty. We accepted the default settings for all driving assist options except for the transmission, which we set at manual. We chose the manual transmission (rather than automatic) to increase drivers' involvment in the game. The camera/viewpoint was set within the car (i.e., driver's-eye view), and the head-up display options were turned off, except for the speedometer. There were no other cars on the road. The sound was on for both Drivers and Passengers.

We used a between-participants, yoked control design with individual Passengers being yoked to individual Drivers. Odd numbered participants were assigned to the driver group and even numbered participants were assigned to the Passenger group. The recording from Participant 1 was viewed by Participant 2, the recording from Participant 3 was viewed by Participant 4, and so on.

The driver group was similar to our previous studies of motion sickness among players of console video games (Merhi et al. 2007; Stoffregen et al., 2008); the main difference was that in previous studies we did not use driving games. The passenger group resembled mainstream studies of visually induced motion sickness (Draper, Viirre, Gawron, & Furness, 2001; Duh, Parker, Philips, & Furness, 2004; Stoffregen & Smart, 1998) in the sense that participants did not control the visual motion and were instructed only to watch it.

Researchers often do not distinguish between the incidence of motion sickness and the severity of motion sickness symptoms. Severity measures (e.g., symptom ratings) are continuous and this feature can sometimes be an advantage. Our study was based on the postural instability theory of motion sickness (Riccio & Stoffregen, 1991), which makes predictions about differences in postural activity between persons who are experiencing motion sickness and those who are not. Because the predictions are formulated in this way, testing of the predictions requires that we compare postural activity in Sick and Well groups and, therefore, that we adopt a dichotomous sick/well classification, rather than a graded scale. For this reason, we assessed motion sickness incidence by asking participants to make forced choice, yes/no statements about whether they were motion sick (e.g., Bonnet et al., 2006; Faugloire et al., 2007; Stoffregen et al., 2008; Stoffregen & Smart, 1998). Participants were divided into Sick and Well groups based on these explicit verbal statements. Participants were informed that they could discontinue at any time for any reason. Thus, there was no motivation for them to give false reports of motion sickness as a means to discontinue participation.

We evaluated the severity of motion sickness symptoms using the Simulator Sickness Questionnaire, or SSQ (Kennedy et al., 1993). The SSQ was designed to assess the severity of a variety of symptoms that are often associated with motion sickness, such as fatigue, eyestrain, vertigo, and nausea. We administered the SSQ before the game session, and again afterward (Bonnet et al., 2006; Stoffregen & Smart, 1998). The initial administration ensured that participants were familiar with the symptoms of motion sickness and provided baseline data. We have sometimes found disjunction between reports of motion sickness incidence, on the one hand, and symptom severity on the other (e.g., Merhi et al., 2007). This disjunction supports our practice of reporting both the incidence of motion sickness and the severity of symptoms.

Only one person participated at a time. After completing the informed consent form, participants filled out a video game experience questionnaire and the SSQ. They were informed that they could discontinue at any time, for any reason, and were asked to discontinue immediately if they felt any symptoms of motion sickness, however mild. Participants were given a brief introduction to the Xbox system and to the controls in *Forza Motorsport 2*. Drivers practiced controlling the device for 5 minutes. Within this practice session drivers were free to ask questions about the game or the controls. At the end of the practice session no driver indicated that they had any problem using the controls. Passengers watched a 5-minute practice session pre-recorded by the Experimenter.

We asked participants to avoid unnecessary movement. Participants then played or viewed *Forza Motorsport 2* continuously for up to 40 min. Participants were reminded to discontinue immediately if they experienced any symptoms of motion sickness, however mild. Data on head and torso motion were collected continuously throughout the game session. At the end of 40 min (or at the time of discontinuation) participants were asked to state, yes or no, whether they were motion sick, after which they filled out the SSQ a second time. When a driver discontinued, his or her recording was played to the corresponding passenger. If that passenger had not discontinued by the end of the (truncated) recording, the recording was re-started and replayed automatically until 40 minutes were completed or until the passenger discontinued, whichever came first.

Data Analysis

We classified individual participants as being sick or well based on their yes/no statements. We quantified the severity of symptoms using the Total Severity Score of the SSQ, which we computed in the recommended manner (Kennedy et al., 1993).

We analyzed movement of the head and torso in the fore-aft or anteroposterior (AP) axis, and in the side-to-side or mediolateral (ML) axis. To address effects relating to the magnitude of movement we evaluated positional variability, which we operationalized as the standard deviation of position. Magnitude measures are useful but do not permit analysis of the temporal structure of movement, that is, of temporal dynamics. Movement magnitude can differ qualitatively from movement dynamics. There is ongoing debate about the nature and definition of *stability* in human movement (e.g., Bonnet, Faugloire, Riley, Bardy, & Stoffregen, 2006) and, consequently, in the nature of unstable movements that may play a causal role in motion sickness. In previous research we have identified changes in movement dynamics (preceding motion sickness) that differ from changes found in measures of movement magnitude (e.g., Villard et al., 2008). To address effects relating to the dynamics of movement we used detrended fluctuation analysis (DFA). 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 the control of stance (e.g., Riley, Balasubramanium, & Turvey, 1999). We did not integrate the time series before performing DFA. 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 (e.g., more periodic, or more predictable) over time. White noise, which is uncorrelated, yields $\alpha = 0.5$. The presence of long-range autocorrelation is indicated by $\alpha > 0.5$. Pink noise (also known as 1/f noise) is indicated when $\alpha = 1.0$. Values of $\alpha > 1.0$ indicate non-stationary activity that resembles a random walk, while $\alpha > 1.5$ indicates Brownian noise (Chen et al.). Quiet stance in healthy adults tends to be non-stationary, typically yielding $1.0 < \alpha < 1.5$ (Riley et al.).

We also evaluated coupling of movement between members of each pair of participants. Classically, cross-correlation techniques might be used to quantify coupling. However, cross-correlation assumes that the underlying data are linear, an assumption which is routinely violated in data on postural activity (e.g., Duarte & Zatsiorsky, 2000). To quantify interpersonal coupling, we used Average Mutual

Information (AMI), a non-linear form of cross-correlation analysis (for derivation and equations, see Boker, Schreiber, Pompe, & Bertenthal, 1998, and Stoffregen, Villard, Kim, Ito, & Bardy, 2009). AMI estimates the nonlinear dependencies between two time series. As with classical cross-correlation, AMI evalutes these dependencies across a range of time lags between the two time series. The reported value of AMI is the maximum observed dependency from across the spectrum of lags.

Results

Participants reported having played console video games for an average of 12 years (standard deviation = 4 years) and, within the last year, for an average of 2.28 hours per week (standard deviation = 2.37 hours). Participants reported spending the most time playing sports games (basketball, football, Wii sports), followed by adventure games (e.g., *Call of Duty*), and driving games. The only metric for task performance that was available from *Forza Motorsport 2* was the number of laps completed, which (for a given session duration) was related to speed). Across all Drivers, the mean number of laps completed was 10.46 (minimum = 5, maximum = 15).

Subjective Reports

The overall incidence of motion sickness was 42.3% (11 Sick, 15 Well). Motion sickness incidence was greater among Passengers (69.2%; 9 Sick, 4 Well) than among Drivers (15.4%; 2 Sick, 11 Well), $\chi^2_{(1)} = 7.72$, $p < 0.05$.

Table 1 gives the status of members of each pair of participants. All possible combinations of Sick and Well occurred. Thus, there was no evidence of behavioral contagion.

A total of 11 participants discontinued, with a mean time of discontinuation of 17.25 minutes. Two Drivers discontinued, one after 16.42 (after completing 5 laps) and the other after 36.29 minutes (after completing 15 laps). For the nine Passengers who discontinued, the mean time of discontinuation was 15.23 minutes, after viewing a mean of 10.22 laps. Each participant who discontinued stated that they were motion sick. Fifteen participants completed the 40-minute game session; none reported motion sickness. None of the participants reported becoming motion sick within 24 hours after leaving the laboratory.

Data on symptom severity are presented in Table II. Pre-exposure scores were low, and did not differ between Drivers and Passengers, or between participants who later reported motion sickness and those who did not. Post-exposure scores were higher than pre-exposure scores for each group (Well group, $Z = -3.408$, $p < 0.05$; Sick group, $Z = -2.934$, $p < 0.05$; Drivers, $Z = -3.180$, $p < 0.05$; Passengers, $Z = -3.180$, $p < 0.05$), revealing that exposure to the game increased symptoms.

At post-exposure, SSQ scores were higher for the Sick group than for the Well group (Mann-Whitney $U = 18$, $p < 0.05$).

Movement Data

We analyzed the movement data using a windowing procedure that permitted us to examine the evolution of movement over time during exposure to the console video game (Stoffregen et al., 2008). We examined three non-overlapping time windows (each 2 minutes in duration) selected from the beginning, middle, and end of the exposure. For this reason, we could include in our analysis only participants who were exposed to the game for six minutes or more. Two participants in the Sick group (both passengers) discontinued after being exposed to the game for less than six minutes and, therefore, were excluded (together with their corresponding drivers) from our analyses of the movement data. Among the remaining participants in the Sick group the mean exposure duration was 19.3 minutes.

For the Sick group, we choose the first, the middle, and the final two minutes for each participant. Due to discontinuation, participants in the Sick and Well groups did not have the same duration of exposure to the game. We judged it to be important to ensure that the windows for the Sick and Well groups represented similar exposure durations. To ensure this we tied the selection of windows for the Well group to the 19.3-minute mean exposure duration of the Sick group. Accordingly, the 1st, 2nd, and 3rd time windows extended from 0 – 2 minutes, 8.6 – 10.6 minutes, and 17.3 – 19.3 minutes, respectively. This selection ensured that the average exposure duration was similar for the Sick and Well groups.

The independent variables were Control (Drivers vs. Passengers), Sickness Group (sick vs. well), and Time Windows (1st, 2nd, and 3rd). The dependent variables were the positional variability of movement (operationalized as the standard deviation of position), and the predictability of movement (operationalized as α of DFA), computed separately for the AP and ML axes of the head and torso.

In the AP axis, the main effect of time windows was significant for positional variability of the head, $F(2,40) = 3.29$, $p < .05$, partial $\eta^2 = 0.14$ ($\text{Mean}_{\text{First Window}} = .57$, $SD = .36$; $\text{Mean}_{\text{Second Window}} = .67$, $SD = .51$; $\text{Mean}_{\text{Third Window}} = .72$, $SD = .61$). For head movement in the AP axis there was a significant interaction between sickness groups and time windows, $F(2,40) = 4.47$, $p < .05$, partial $\eta^2 = 0.18$, which is illustrated in Figure 1

A. Across time windows, variability in the Sick group tended to increase, while in the Well group movement remained stable over time. The sickness group × time windows interaction was also significant for AP movement of the torso, $F(2,40) = 5.10$, $p < .05$, partial $\eta^2 = 0.20$ (Figure 1 B).

In the ML axis, the main effect of Control was significant for positional variability of the head, $F(1,20) = 7.69$, $p < .05$, partial $\eta^2 = 0.28$, and of the torso, $F(1,20) = 8.98$, $p < .05$, partial $\eta^2 = 0.31$. In both cases, there was more movement among Drivers than among Passengers (Figure 2).

Detrended fluctuation analysis revealed several effects on α. The main effect of time windows was significant for head movement in the AP axis, $F(2,40) = 4.02$, $p = .026$, partial $\eta^2 = 0.17$, and in the ML axis, $F(2,40) = 4.41$, $p = .024$, partial $\eta^2 = 0.18$, and for torso movement in the AP axis, $F(2,40) = 4.19$, $p = .022$, partial $\eta^2 = 0.17$. As shown in Table III, in each case movement became more predictable across time windows.

The main effect of Control was significant for movement of the head in the AP axis, $F(1,20) = 4.58$, $p = .045$, partial $\eta^2 = 0.19$ (Mean $\alpha_{\text{Driver}} = 0.82$; SD = 0.12; Mean $\alpha_{\text{Passenger}} = 0.74$, SD = 0.16), and in the ML axis, $F(2,20) = 7.59$, $p = .012$, partial $\eta^2 = 0.28$ (Mean $\alpha_{\text{Driver}} = 0.80$; SD = 0.12; Mean $\alpha_{\text{Passenger}} = 0.67$, SD = 0.15), as well as for movement of the torso in the ML axis, $F(2,20) = 10.48$, $p = .004$, partial $\eta^2 = 0.34$ (Mean $\alpha_{\text{Driver}} = 0.68$; SD = 0.12; Mean $\alpha_{\text{Passenger}} = 0.52$, SD = 0.16). In each case, there was greater predictability or self-similarity among Drivers than among Passengers.

In the ML axis, the interaction between Control and Time Windows was significant for movement of the head, $F(2,20) = 4.24$, $p = .027$, partial $\eta^2 = 0.18$, and for movement of the torso, $F(2,40) = 4.27$, $p = .022$, partial $\eta^2 = 0.18$. In each case, Drivers' movement did not change over time, while the movement of Passengers tended to become more predictable over time (Figure 3).

Coupling between Drivers and Passengers

We used AMI to quantify the degree of coupling between movements of drivers and passengers. Computation of coupling between Drivers and Passengers required 1:1 matching of data points for the two participants in each pair. We could not do this for pairs in which the passenger continued after the driver had discontinued. For this reason, we excluded from the AMI analysis one pair of participants in which the driver discontinued. Thus,we contrasted pairs in which both driver and passenger were well (Well-Well) with pairs in which the driver was well and the passenger was sick (Well-Sick). Our analysis included three Well-Well pairs, and seven Well-Sick pairs. We examined values of lag up to and including 10 s.

The absolute value of the maximum observed lag was 4.68 s. We found a significant main effect of passenger sickness on head movements in the AP axis, $F(1,8) = 6.65$, $p < .05$, partial $\eta^2 = 0.45$. Coupling was stronger in Well-Well pairs (mean maximum AMI = 0.28, SD = 0.14) than in Well-Sick pairs (mean maximum AMI = 0.20, SD = 0.10).

The main effect of time windows was significant for torso movement in the AP axis, $F(2,16) = 5.14$ $p < .05$, partial $\eta^2 = 0.39$, with AMI increasing across windows (1st window mean maximum AMI = 0.18, SD = 0.07; 2nd window mean maximum AMI = 0.16, SD = 0.05; 3rd window mean maximum AMI = 0.23, SD = 0.07).

Discussion

One member of each participant pair drove a virtual automobile that did not include inertial motion. Their performance was recorded and then shown to the other member of the pair, such that members of each pair were exposed to identical visual motion stimulation. Drivers were less likely to report motion sickness than Passengers. Thus, user control reduced the risk of motion sickness in non-inertial virtual vehicles. Drivers engaged in more bodily movement (and more predictable movement) than Passengers. At the same time, movement differed between participants who (later) reported motion sickness and those who did not. We discuss these results in turn.

Motion Sickness and Vehicular Control

In our yoked control design, motion sickness was reported by 69.2% of passengers, but by only 15.4% of drivers. This result confirms that vehicular control is an important factor in motion sickness etiology, and extends this finding to the control of virtual vehicles that do not include inertial displacement. The similarity of effects between physical and virtual vehicles indicates that the influence of control on susceptibility is not limited to the control of inertial vehicular motion.

Rolnick and Lubow (1991) argued that active control generates “feed-forward” information that is used to “process the motion stimuli more efficiently” (p. 870), so that motion sickness should be less common among drivers than among passengers. By contrast, Oman (1982) claimed that active control is the primary source of the internal expectations that are the referent for the existence and magnitude of sensory conflict. For this reason, Oman argued that active control should lead to more motion sickness, rather than less. Both Oman and Rolnick and Lubow espoused the sensory conflict theory of motion sickness, and so it appears that there is not a consensus among proponents of sensory conflict about how to interpret the influence of vehicular control on the incidence of motion sickness. Our interpretation of this effect is offered in a later section.

The low incidence of motion sickness among drivers contrasts with previous studies using non-vehicular console video games, in which motion sickness incidence has been much higher (50%: Merhi et al., 2007; 100%: Stoffregen et al., 2008). The difference may stem from differences between games; not all games are equally nauseogenic (Merhi et al.). Alternatively, it may be that control of virtual vehicles is less nauseogenic than control of virtual non-vehicular locomotion, such as walking or running. For a given video game the incidence of motion sickness can be higher when players stand than when they sit (Merhi et al.), which suggests that motion sickness may be influenced by variations in the control of body posture relative to the virtual environment. This issue will be an important area for future research. For example, it would be interesting to examine the effects on motion sickness and postural activity of standing vs. sitting for passengers (i.e., viewers of driving video games) as compared to participants who view non-vehicular video games.

Movement of Sick Versus Well

Among participants who later reported motion sickness, positional variability tended to increase over time during exposure to the video game, relative to participants who did not report motion sickness (Figure 1). This result confirms our prediction and is consistent with the postural instability theory of motion sickness (Bonnet et al., 2006; Faugloire et al., 2007; Riccio & Stoffregen, 1991). This result might be interpreted from the perspective of sensory conflict (e.g. Reason & Brand, 1975; Rolnick & Lubow, 1991), but such an interpretation would need to take into account the fact that differences in the movement of well and sick participants existed prior to the onset of subjective motion sickness symptoms.

Coupling of head movements between drivers and passengers was stronger when both members of a pair were well, and weaker when the passenger later reported motion sickness. Because drivers and passengers participated separately it is unlikely that they could directly or intentionally couple their movements with each other. For this reason, data on coupling between members of a pair can be interpreted in terms of coupling between individuals and game motion. Thus, the coupling analysis provides evidence that, as individuals, well and sick participants differed in the strength of coupling between their head movements and events in the game.

Movement effects relating to motion sickness were limited to the AP axis (positional variability, and AMI). By contrast, differences in movement between drivers and passengers appeared in the ML axis (positional variability and α of DFA; the sole exception was α for AP head movement). This distinction suggests that unstable movement related to motion sickness was confined to one axis (AP). One possible explanation for this effect is that motion sickness was related to linear acceleration (changes in vehicle speed, which corresponded to movement along the body's AP axis) and not to angular acceleration (turns, which corresponded to movement in the body's ML axis). Another possibility is that participants focused on attempting to stabilize movements in the body’s ML axis and exercised less control over movement in the body’s AP axis. In previous research using both video games and laboratory devices motion sickness has been preceded by changes in bodily movement in one or both of these axes (e.g., Merhi et al., 2007; Stoffregen et al., 2008; Stoffregen & Smart, 1998). How these variations in the axes of unstable movement may relate to vehicular and non-vehicular motion, and to user control of motion will be important topics for future research.

We did not find differences between the Sick and Well groups in the dynamics of movement as quantified using DFA. That is, prior to the onset of subjective symptoms of motion sickness the predictability of movement did not differ between participants who later reported motion sickness and those who did not. The difference in outcomes for our analyses of movement magnitude and coupling, on the one hand, and DFA on the other underscores the value of separately evaluating these aspects of movement. Postural activity is highly complex and can be characterized using a wide variety of dependent measures. Three previous studies have examined both positional variability and DFA in the context of motion sickness (Bonnet et al., 2006; Stoffregen, Yoshida, Villard, Scibora, & Bardy, 2010; Villard et al., 2008). In some cases, parallel effects relating to magnitude and dynamics have been found (i.e., a given main effect or interaction influenced both positional variability and DFA), but in other cases positional variability and DFA were affected independently. None of those earlier studies involved video games or the motion of either physical or virtual vehicles. These differences in experimental method may account for the fact that in the present study sick and well participants differed in movement magnitude but not in movement dynamics. Additional resesarch will be needed to determine the exact parameters of postural activity that precede motion sickness. Among other things, it will be important to determine whether motion sickness across situations (e.g., physical vs. virtual vehicles) is related to changes in a single parameter of movement or to multiple parameters of movement. Such analyses can contribute to our understanding of motion sickness etiology, but also to broader questions about the nature and definition of stability in instability in animate movement.

Movement of Drivers Versus Passengers

Drivers engaged in more bodily movement than passengers (Figures 2 and 3). This result is not surprising, given that drivers were involved in game play; however, it may have implications for the nature of changes in body movement the precede motion sickness. The greater movement observed among drivers, combined with the finding that drivers were less likely than passengers to report motion sickness, suggests that motion sickness was not related to the overall magnitude of participants' movements (Riccio & Stoffregen, 1991). Drivers and passengers also differed in movement dynamics, as revealed by DFA. The movement of drivers was more self-similar or predictable than the movement of passengers. Future research will be needed to understand these differences in movement between drivers and passengers, and whether differences in movement are related to the fact that drivers and passengers are differentially susceptible to motion sickness.

Vehicular Control Versus Postural Control

Our finding of reduced motion sickness incidence among drivers (relative to passengers) can be explained in terms of constraints on control of the body within a moving vehicle. In vehicular travel only the driver controls the vehicle but each person must maintain the stability of his or her own body. Thus, motion sickness may be preceded by unstable control of the body in drivers or in passengers. As shown by

Rolnick and Lubow (1991) control of a physical vehicle reduces the risk of motion sickness, an effect that we have replicated in the context of virtual vehicles. The reduced incidence of motion sickness among drivers of both physical and virtual vehicles suggests that having control of a vehicle may increase the driver's ability to stabilize his or her body, consistent with the postural instability theory of motion sickness (Riccio & Stoffregen, 1991). One possibility is that drivers are able to maintain more stable coupling between motion of the vehicle (relative to the environment) and motion of the body (relative to the vehicle). Coupling might be quantified using any of a variety of measures, such as the relative phase between oscillations of the vehicle and the body (e.g., Bardy, Marin, Stoffregen, & Bootsma, 1999), average mutual information (Stoffregen et al., 2009), or cross-recurrence quantification (e.g., Shockley et al., 2003).

Generalized Side Effects of Exposure to Virtual Environments

Exposure to virtual environments can lead to a variety of side effects, including subjective experiences and changes in body movement. Some level of post-exposure side effects is reported by 80% to 95% of persons exposed to virtual environment systems (Stanney et al., 1998). Not all of these subjective experiences are related to motion sickness. For example, head mounted displays can give rise to headache and eyestrain in the absence of motion sickness (e.g., Draper et al., 2001; Merhi et al., 2007). The SSQ indexes symptoms, such as general discomfort, fatigue, eyestrain, and blurred vision, that characterize motion sickness but which also occur in the absence of motion sickness. We found a statistically significant increase in SSQ scores from pre- to post-exposure for Well participants; that is, scores rose among participants who stated that they were not motion sick. The SSQ is a reliable measure of the severity of subjective symptoms that are associated with motion sickness. However, our results suggest that the SSQ may not be sensitive to differences between motion sickness and other subjective aftereffects of exposure to virtual environments (cf. Merhi et al., 2007; Stoffregen et al., 2008; cf. Stanney & Hash, 1998).

In addition to subjective aftereffects, virtual environments can bring about changes in body movement, such as visually guided reaching, and the control of standing posture. Changes in movement can be but are not always associated with subjective aftereffects (Stanney et al., 1998). This is true even for relations between movement aftereffects and motion sickness. For example, prolonged exposure to virtual environments is associated with generalized increases in postural activity (e.g., Akiduki et al., 2000; Kennedy, Berbaum, & Lilienthal, 1997; Kennedy, Fowlkes, & Lilienthal, 1993; Kennedy & Stanney, 1996), and with changes in the dynamics of body sway (e.g., Bonnet et al., 2006; Villard et al., 2008) regardless of whether or not participants reported motion sickness. In the present study, main effects of Time Windows were of this type: Movement changed across time windows for both Sick and Well participants. In addition, movement changed over time differently for drivers and passengers (Figure 3). These effects are independent of other changes in bodily movement that preceded the onset of motion sickness and occur only among individuals who became motion sick (Figure 1; see also Bonnet et al., 2006; Stoffregen & Smart, 1998). In the present study, motion sickness was preceded by changes in the variability of head and torso movement, and by changes in the coupling of body movement to the video game. Taken together, these studies show that visual motion can affect multiple parameters of postural activity, and that some of these affects are associated with subsequent motion sickness while others are not. This finding underscores the importance of evaluating multiple parameters of postural activity (e.g., both linear and nonlinear), and of classifying participants into Sick and Well groups when analyzing postural data.

Motion Sickness, Simulator Sickness, or Cybersickness?

There is a long history of debate about whether the field of study concerns a single malady that appears in multiple situations (i.e., motion sickness) or different maladies that occur in different situations (e.g., motion sickness, simulator sickness, cybersickness, Space Adaptation Syndrome). Our sympathies lie with the former, that is, we claim that motion sickness is a single malady with a single etiology, which occurs in different situations. Consistent with this claim, we have studied relations between postural activity and motion sickness in Air Force flight simulators (Stoffregen et al., 2000), in virtual environments (Villard et al., 2008), in laboratory devices (Stoffregen & Smart, 1998), and in console video games (Stoffregen et al., 2008). In every case, we have found that self-reports of motion sickness have been preceded by changes in one or more parameters of postural activity. In promulgating the postural instability theory of motion sickness, Riccio and Stoffregen (1991) addressed this issue directly, reviewing different situations that are associated with motion sickness (including simulators) and arguing for a single etiology. In this regard our view is similar to other explicit theories of motion sickness etiology; examples include Reason (1978), Oman (1982), and Bles et al. (1998). Scholarly discussions of simulator sickness commonly are explicit in describing it as a form of motion sickness (e.g., Kennedy & Fowlkes, 1992, who do this repeatedly), and in linking its etiology to theories of motion sickness etiology (e.g., Kennedy, Hettinger, & Lilienthal, 1990). That being said, a fundamental premise of the present study is that it is not proper to assume that research with physical vehicles will generalize to motion sickness in simulated vehicles. Our study can be interpreted as a test of the hypothesis that the phenomena of motion sickness in physical vehicles will differ from the phenomena of motion sickness (or simulator sickness) in virtual vehicles. We found no evidence to support this hypothesis.

Conclusion

The present study has both practical and theoretical implications. Rolnick and Lubow (1991) used a purpose-built whole-body motion device that moved only in rotation, and only in one axis. The expense and complexity of creating whole body motion devices for laboratory research are important factors in the paucity of research relating motion sickness etiology to the control of physical vehicles. Our method, using console video games, offers a more practical and more flexible way to study the influence of user control on motion sickness while minimizing the risk of behavioral contagion. Rolnick and Lubow demonstrated that motion sickness susceptibility is influenced by user control of physical vehicles. We have shown that a similar effect obtains with the control of non-inertial virtual vehicles in console video games. The generality and robustness of the influence of vehicular control confirms its importance in any theoretical explanation of motion sickness (Reason & Brand, 1975).

We focused on relations between control of the vehicle, on the one hand, and control of the body, on the other. The data revealed that drivers tended to move more than passengers, and that the movements of drivers were more predictable or self-similar. Independent of these effects, we identified changes in the magnitude body movement and in the coupling of body movement with the video game that were uniquely associated with participants (both drivers and passengers) who later reported motion sickness. These results suggest that motion sickness might be predicted through online monitoring of appropriate parameters of postural activity (cf. Smart, Stoffregen, & Bardy, 2002). Our results are consistent with the hypothesis that control of vehicular motion makes it easier for drivers to maintain stable control of their bodies, which in turn reduces the risk of motion sickness (Riccio & Stoffregen, 1991).

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Table I

Motion sickness incidence for individual participants, indicating the time of discontinuation (minutes)

Participant Pair

	1	2	3	4	5	6	7	8	9	10	11	12	13
Driver					16.42				36.29				
Passenger		36.75	5.51			22.89	21.91	12.09	3.74		11.70	13.73	8.74

Note. Empty cells represent Well participants. Cells with entries indicate participants who stated that they were motion sick. Each participant who discontinued stated that they were motion sick.

Table II

Total Severity Scores for the Simulator Sickness Questionnaire

			Pre-exposure		Post-exposure	
		N	Mean	SD	Mean	SD
Drivers	Well	11	25.89	35.01	110.28	65.87
	Sick	2	55.12	27.86	183.99	76.01
Passengers	Well	4	25.68	24.56	126.49	26.33
	Sick	9	19.83	15.61	172.84	46.43

Note. The maximum possible score on the SSQ was 235.62.

Table III

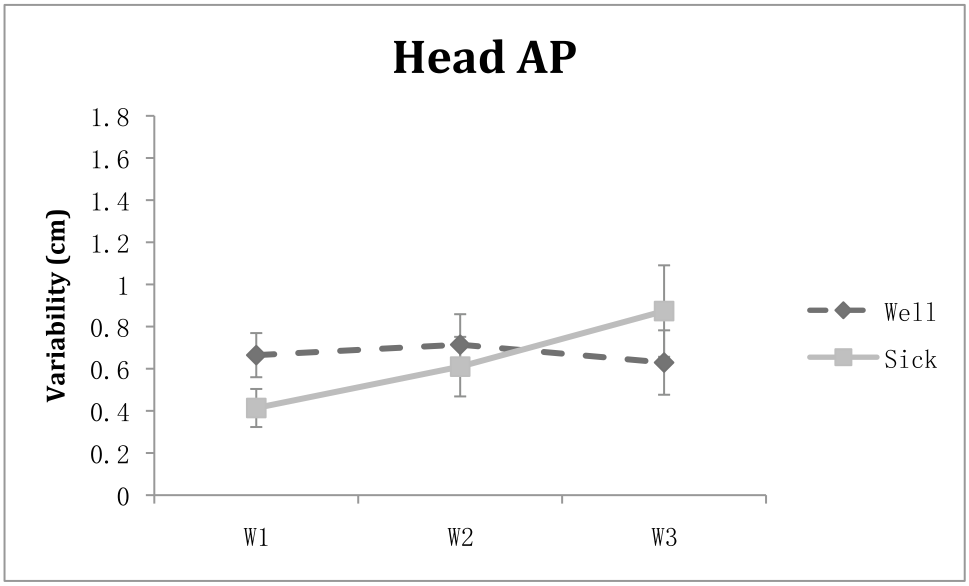
Main effects of time windows on α of DFA

	Window 1		Window 2		Window 3	
	Mean	SD	Mean	SD	Mean	SD
Head AP	0.73	0.13	0.81	0.15	0.81	0.14
Head ML	0.69	0.16	0.76	0.15	0.78	0.13
Torso AP	0.60	0.17	0.65	0.15	0.68	0.14

Note. AP: Anterior-posterior axis. ML: Mediolateral axis. For the Sick group, Windows 1, 2, and 3 represented the first, middle, and final 2 minutes for each individual. For the Well group, Window 1: 0 – 2 minutes; Window 2: 8.6 – 10.6 minutes; Window 3: 17.3 minutes – 19.3 minutes.

Figure 1. Positional variability in the AP axis, illustrating the significant sickness group × time windows interactions. A. Head movement. B. Torso movement. Error bars represent standard error.

A.



B.

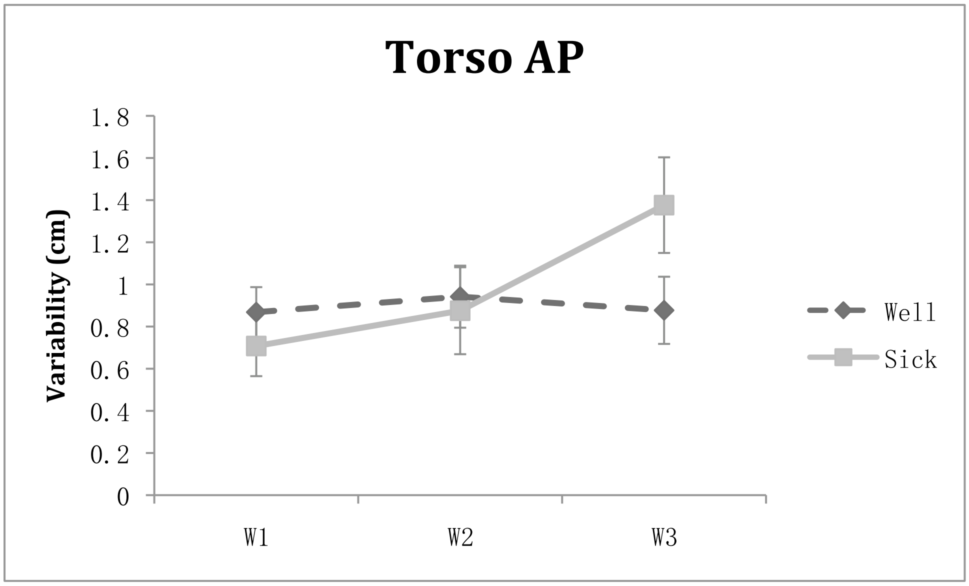


Figure 2. Positional variability in the ML axis. A. Head movement. B. Torso movement. Error bars represent standard error.

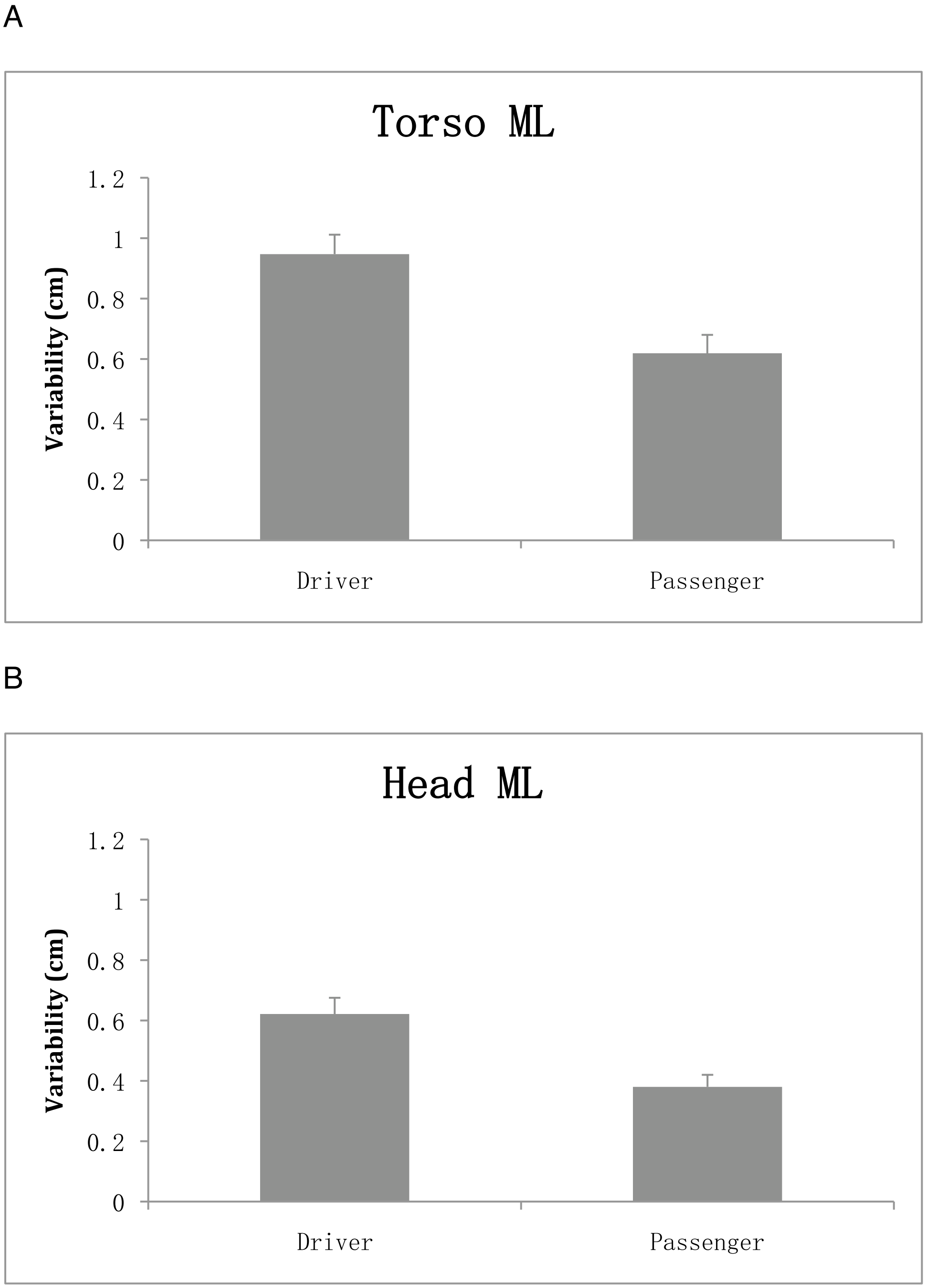
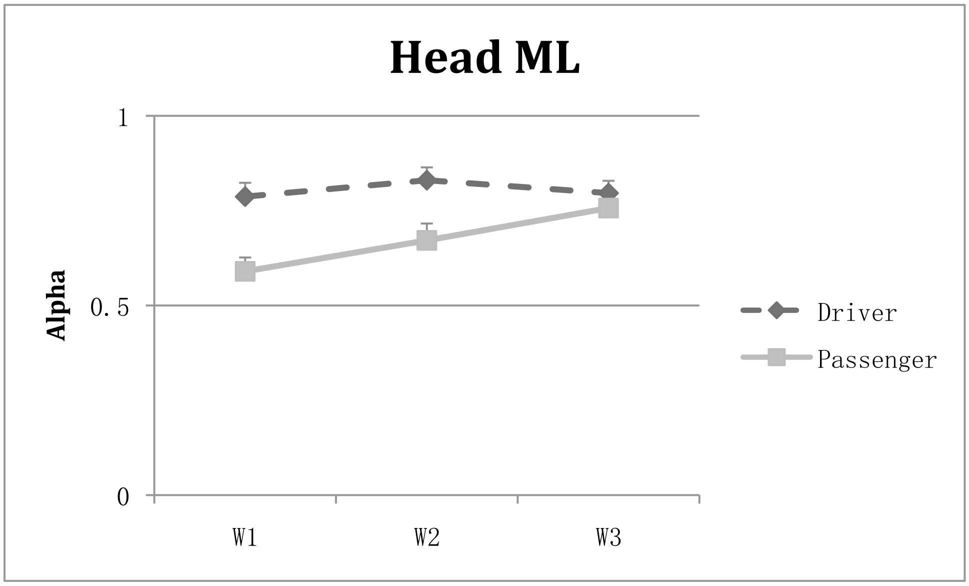


Figure 3. Interactions between Time Windows and Driver/Passenger for α of DFA in the ML axis. A. Head movement. B. Torso movement. Error bars represent standard error.

A.



B.