Exp Brain Res (2014) 232:1389–1397
DOI 10.1007/s00221-014-3859-3

RESEARCH ARTICLE

Motion control, motion sickness, and the postural dynamics of mobile devices

Thomas A. Stoffregen · Yi-Chou Chen · Frank C. Koslucher

Received: 13 November 2013 / Accepted: 28 January 2014 / Published online: 7 February 2014

Abstract Drivers are less likely than passengers to experience motion sickness, an effect that is important for any theoretical account of motion sickness etiology. We asked whether different types of control would affect the incidence of motion sickness, and whether any such effects would be related to participants' control of their own bodies. Participants played a video game on a tablet computer. In the Touch condition, the device was stationary and participants controlled the game exclusively through fingertip inputs via the device's touch screen. In the Tilt condition, participants held the device in their hands and moved the device to control some game functions. Results revealed that the incidence of motion sickness was greater in the Touch condition than in the Tilt condition. During game play, movement of the head and torso differed as a function of the type of game control. Before the onset of subjective symptoms of motion sickness, movement of the head and torso differed between participants who later reported motion sickness and those that did not. We discuss implications of these results for theories of motion sickness etiology.

Keywords Posture · Postural control · Motion sickness · Human–computer interaction

Introduction

Susceptibility to motion sickness is lower among people who control motion stimuli than among people—exposed to the same motion—who do not control it. A common anecdotal report is that drivers are less likely than passengers to become motion sick. This observation has been verified in controlled laboratory research in the context of physical vehicles (Rolnick and Lubow 1991), virtual vehicles (Dong et al. 2011), and virtual ambulation (Chen et al. 2012). In existing research, control has been treated as a dichotomous variable: Participants either exerted control over motion stimulation (e.g., drivers) or did not (e.g., passengers). In the present study, we asked whether motion sickness susceptibility could be influenced by different types of motion control. We also conducted the first experimental test of the hypothesis that tablet computers can give rise to motion sickness. Finally, we related motion control and motion sickness to patterns of postural activity.

Motion control in motion sickness etiology

Theories of motion sickness acknowledge an important etiological influence of motion control (e.g., Oman 1982; Reason 1978). Discussions of the role of motion control have treated control as a dichotomous variable. In relation to anecdotal reports, this dichotomous classification makes sense because there is a qualitative (i.e., dichotomous) distinction between drivers (who control vehicle motion) and passengers (who do not). This dichotomous distinction has been preserved in empirical research (Chen et al. 2012; Dong et al. 2011; Rolnick and Lubow 1991; cf. Stanney and Hash 1998). However, control of motion need not be dichotomous. In particular, a person can control some aspects of motion but not others. As one example, a driver controls the automobile's velocity and trajectory, but exerts little or no control over vertical oscillation (e.g., ascending and descending hills) or overall vehicle vibration. Low-frequency oscillatory motion is closely associated with motion

T. A. Stoffregen (✉) · Y.-C. Chen · F. C. Koslucher
School of Kinesiology, Cooke Hall, University of Minnesota, Minneapolis, MN 55455, USA
e-mail: tas@umn.edu

sickness (e.g., Guignard and McCauley 1990; Lawther and Griffin 1986).

While only the driver controls the automobile, both drivers and passengers must stabilize their own bodies. Control of the body powerfully affects motion sickness incidence not only when participants control the visual motion stimulus, but also when they do not (Chang et al. 2013; Dong et al. 2011; cf. Littman et al. 2010). Thus, control of the nominal stimulus is not the sole type of control that affects motion sickness incidence. Accordingly, new research investigating relations between motion sickness and different types of control can aid understanding of motion sickness etiology, in general. In the present study, we took this issue in a new direction, made possible by developments in computer technology.

New types of control

Our manipulation of control was not only motivated by theoretical considerations, but also by changes in technology. We are in the midst of a technological transformation in computer displays and interactivity. Until recently, computer displays were of the "desktop" variety, in which the display screen was stationary relative to the earth. Manual control inputs (i.e., through a mouse, joystick, or gamepad) influenced the contents of displays, but had no effect on the position or motion of the display unit itself. With the advent of handheld mobile devices, millions of people now interact with computer displays that are not earth-stationary, such as smartphones and tablet computers. Typically, these devices incorporate sensors that detect motion of the device and software applications that use this information to update the contents of visual displays in real time. That is, physical motion of the display device can be used as an input to control the contents of the display. With these devices, manual control inputs can affect display contents in two qualitatively different ways, by touching the screen and by moving the device.

Previous research relating control of a display to control of the body has focused on traditional, all-or-nothing manipulations of control (for a rare exception, see Stanney and Hash 1998). These studies showed that participants who controlled a virtual display moved more than participants who did not and that their movements exhibited different temporal dynamics (Chen et al. 2012; Dong et al. 2011). In the present study, we asked how different types of display control would affect postural activity during game play.

Video games and motion sickness

Motion sickness is common among users of virtual environments, in general (Stanney et al. 1998) and among players of contemporary video games, in particular. Existing research has focused on situations in which the display unit was stationary relative to the earth (e.g., a video monitor; Stoffregen et al. 2008) or relative to the head (e.g., a head-mounted display; Draper et al. 2001; Merhi et al. 2007). Researchers have not addressed the nauseogenic potential of touch screen technologies, or of handheld devices. Anecdotal reports suggest that motion sickness can occur with handheld devices (e.g., Daily Mail 2013). The widespread use of handheld devices to play video games raises questions about relations between video games, handheld devices, and motion sickness.

Susceptibility and control of the body

Chen et al. (2012) and Dong et al. (2011) evaluated the kinematics of bodily movement during exposure to video games. Movement of the head and/or torso differed between participants who later reported motion sickness and those who did not, confirming studies in which motion sickness was induced by laboratory devices (e.g., Smart et al. 2002; Stoffregen et al. 2010). This was true for participants who controlled the display and for participants who did not control the display. In the present study, we monitored movement of unrestrained participants during game play to determine whether these relations would occur with variations in the nature of control.

The present study

We conducted the first controlled experimental evaluation of the nauseogenic properties of touch screen visual display systems. We predicted that video games would induce motion sickness when played on a tablet computer. We also asked whether the incidence of motion sickness would be influenced by user-controlled motion of the display unit: Some participants held the device in their hands and controlled the game by moving the device, while other players controlled the game solely through fingertip contact with the device's touch screen. During game play, we predicted that the kinematics of the head and torso would differ between the two types of game control. Finally, we predicted that movement of the head and torso would differ between participants who later reported motion sickness and those who did not.

Method

Participants

Thirty-six undergraduates participated in exchange for course credit. There were 22 females and 14 males, with mean age 21.28 ± 2.72 years, mean height 169 ± 11.8 cm, and mean weight 68.61 ± 13.08 kg.

Apparatus

Games were played on a tablet computer (iPad 2, Apple Inc., Cupertino CA). Data on movement of the head and torso were collected using a magnetic tracking system (FasTrak, Polhemus Inc., Colchester VT). The emitter was placed on a stand 1.5 m above the floor and approximately 0.75 m behind the participant's head. One sensor was attached to the back of a rock-climbing helmet, which participants wore with a snug chinstrap. Another was affixed to the skin, using cloth medical tape, at the level of the seventh cervical vertebra (i.e., between the shoulder blades). Data on the position of each sensor in the anterior–posterior (AP) and mediolateral (ML) axes were sampled at 60 Hz and were stored on disk for later analysis.

Procedure

Following the informed consent procedure, participants completed the Simulator Sickness Questionnaire, or SSQ (Kennedy et al. 1993), which allowed us to assess the initial level of symptoms (SSQ1). They also responded to a forced-choice, yes/no question, *Are you motion sick?* Participants were instructed to discontinue the experiment immediately upon experiencing any motion sickness symptoms, however, mild. Each participant indicated how many years they had been playing any type of video game: mobile device, console, or desktop.

Participants played *Modern Combat 3*, a first person shooter game, while seated at a table. Within the game, each participant played "Mission 6: Dragon king of the sea." Game controls were set to the easy mode. Participants were given up to 10 mins to play a built-in mission tutorial, so as to familiarize themselves with the game and with the manual controls.

In a between-participants design, there were two conditions. In the Touch condition, the iPad was supported by a metal bookstand (at an angle of 45°) such that it was always stationary. Participants gripped the device with both hands but could not physically move it. They controlled the game using only fingertip contact with the screen. In the Touch condition, the fingers of the left hand were used to control avatar locomotion (locomotion vs. standing still) and locomotor speed (walking vs. running). Fingers of the right hand were used to control the avatar's orientation (looking or moving in different directions), as well as all weapon functions (aiming, triggering, throwing). In the Tilt condition, the iPad was again gripped in both hands but was supported only by the hands, and participants were able to move the device rotating their wrists. In the Tilt condition, bimanual tilting of the device was used to control the avatar's orientation, as well as aiming. The fingers of the left hand were used to control the presence and speed of locomotion. The fingers of the right hand were used to control triggering and throwing.

In both conditions, participants were required to maintain both forearms in contact with the table at which they were sitting. This restriction was a departure from naturalism, but we adopted it so as to ensure that only hand (finger and wrist) movements were used in controlling the game. It also helped to equalize the visual angle of the iPad display screen, by maintaining the device within the range of 48–60 cm from the eyes.

Upon discontinuation or after 50 min of game play (whichever came first), participants again answered the forced-choice, yes/no question, *Are you motion sick*? They then completed the SSQ a second time (SSQ2). Participants who stated that they were not sick at SSQ2 were given a printed copy of the SSQ (SSQ3) and asked to fill it out at the time of symptom onset or after 24 h if no symptoms developed.

Data on movement of the head and torso were collected continuously during game play. We did not collect movement data during the pre-game familiarization training.

Analysis of movement data

We evaluated movement of the head and torso in the AP and ML axes. For each of these, we separately evaluated the spatial magnitude and the temporal dynamics of movement. For spatial magnitude, we computed the standard deviation of position. Measures of the spatial magnitude of movement tend to eliminate or discard data on the temporal structure of movement, that is, data on how the measured quantity varied in time. Analyses that preserve information about the temporal structure of data on human movement (that is, analyses of the temporal dynamics of movement) are increasingly common (Lin et al. 2008). We assessed movement dynamics using detrended fluctuation analysis, or *DFA*. DFA describes the relation between the magnitude of fluctuations in postural motion and the time scale over which those fluctuations are measured (Chen et al. 2002). We conducted inferential tests on α, the scaling exponent of DFA, as derived from the movement data. 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 different time-scales. We did not integrate the time series before conducting DFA.

In our ANOVAs, we estimated the effect size using the partial η^2 statistic. According to Cohen (1988), values of partial $\eta^2 > .14$ indicate a large effect and values of partial $\eta^2 > .06$ indicate a medium effect. When the sphericity assumption was violated, the Huynh–Feldt method was used. The Huynh–Feldt method yields fractional degrees of freedom, which we report where appropriate.

Results

Participants were assigned to the Well and Sick groups solely on the basis of their responses to the post-exposure forced-choice question, *Are you motion sick?* Participants were assigned to the Sick group if they answered *yes* in response to this question immediately after game play, or within 24 h after leaving the laboratory.

Incidence and discontinuation

Before game play, each participant stated that they were not motion sick. Following game play, the overall incidence of motion sickness was 31 % (11/36). In the Touch group, motion sickness was reported by 50 % of participants (9/18). In the Tilt group, motion sickness was reported by 11 % of participants (2/18). The incidence of motion sickness was significantly greater among participants in the Touch group than in the Tilt group, $\chi^2 = 6.415$, $p < .05$.

Ten participants discontinued, with a mean time of discontinuation of 35.14 min (SD = 12.52 min). Each participant who discontinued stated that they were motion sick and, accordingly, were included in the sick group. Each participant who was well at the end of the experimental session returned SSQ-3. Of these, one participant reported becoming motion sick after leaving the laboratory and, accordingly, was included in the sick group.

Experience and game performance

Previous experience with video gaming did not differ between Well participants (mean = 9.28 years, SD = 5.50 years) and Sick participants (mean = 6.91 years, SD = 7.30 years), $t(34) = 0.14$, $p > .05$.

For game performance, the dependent variable was the number of times that the avatar was killed. A 2 × 2 ANOVA on conditions (touch vs. tilt) and sickness groups (well vs. sick) revealed a significant main effect of sickness groups, $F(1,1) = 504.83$, $p = .03$, partial $\eta^2 = 0.99$. For participants in the sick group, avatars were killed more often (mean times killed = 15.44, SD = 1.57) than for participants in the well group (mean times killed = 9.28, SD = 0.84). Performance did not differ between the touch and tilt conditions; the interaction also was not significant.

Symptom severity

Data on symptom severity were used exclusively to quantify the magnitude of symptoms reported by the Well and Sick groups. In evaluating symptom severity ratings on the SSQ, we used the Total Severity Score, which we computed in the recommended manner (Kennedy et al. 1993). Data on symptom severity are summarized in Fig. 1. Before game play, the well and sick groups differed slightly, Mann–Whitney $U = 67.5$, $p = .04$. After game play, the well and sick groups differed dramatically, Mann–Whitney $U = 0$, $p < .0001$.

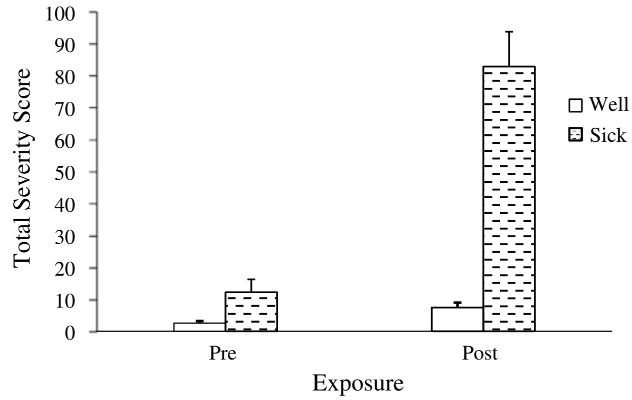

Fig. 1 Symptom severity (mean SSQ total severity score) for the well and sick groups before and after game play. The *error bars* represent standard error of the mean

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 video game (Chang et al. 2012; Dong et al. 2011; Merhi et al. 2007; Stoffregen et al. 2008). We examined three non-overlapping time windows (each 2 min in duration) selected from the beginning, middle, and end of the exposure. In the Sick group, the mean exposure duration was 34.28 min (SD = 13.09 min).

For the Sick group, we chose the first, the middle, and the final 2 min for each participant. Because of 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 34.28-min mean exposure duration of the Sick group. Accordingly, the first, second, and third time windows extended from 0 to 2 min, 16.14 to 18.14 min, and 32.28 to 34.28 min, respectively. This selection ensured that the average exposure duration was similar in the Sick and Well groups.

The independent variables were Control (Touch vs. Tilt), Sickness Group (sick vs. well), and Time Windows (first, second, and third). The dependent variables were the

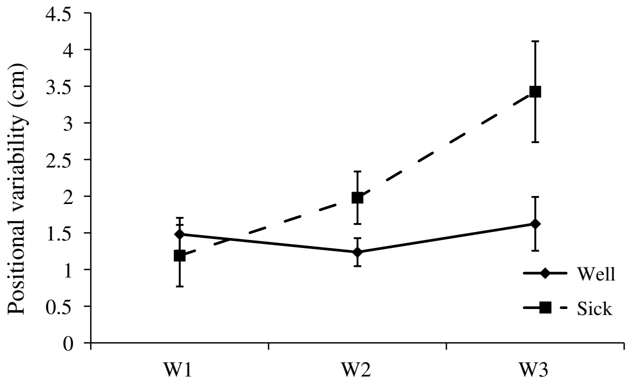

Fig. 2 Statistically significant interaction between sickness groups (well vs. sick) and time windows (W1, W2, W3) for positional variability of the head in the AP axis. The *error bars* represent standard error of the mean

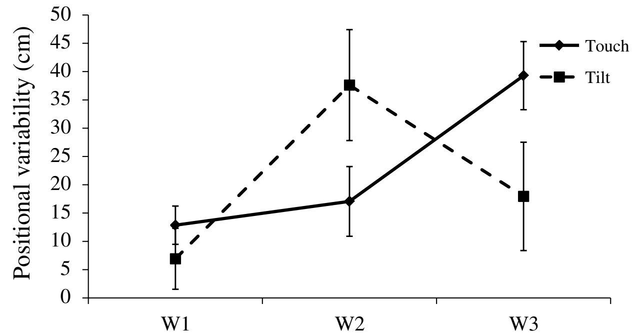

Fig. 3 Statistically significant interaction between conditions (touch vs. tilt) and time windows (W1, W2, W3) for positional variability of the head in the ML axis. The *error bars* represent standard error of the mean

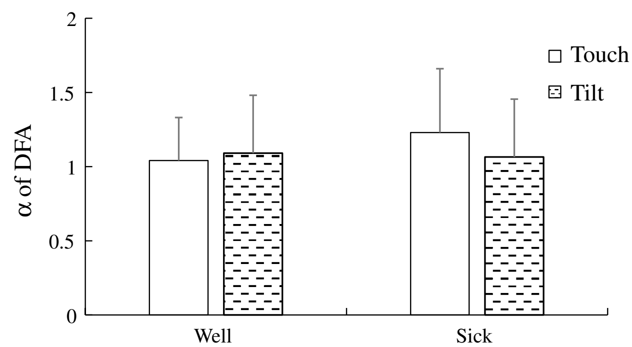

Fig. 4 Statistically significant interaction between sickness groups (well vs. sick) and conditions (touch vs. tilt) for DFA for movement of the head in the AP axis. The *error bars* represent standard error of the mean

positional variability of movement (operationalized as the standard deviation of position) and the self-similarity of movement (operationalized as the DFA), computed separately for the AP and ML axes.

Positional variability of the head

In the AP axis, the main effect of time windows was significant, $F(1.55,64) = 7.72$, $p = .001$, partial $\eta^2 = 0.194$. Positional variability increased over time ($\text{Mean}_{W1} = 1.34$, SD = 0.24; $\text{Mean}_{W2} = 1.61$, SD = 0.20; $\text{Mean}_{W3} = 2.52$, SD = 0.39). The time windows × sickness groups interaction was also significant, $F(1.55,64) = 5.46$, $p = .006$, partial $\eta^2 = 0.146$ (Fig. 2).

In the ML axis, the main effect of time windows was significant, $F(2,64) = 5.99$, $p = .004$, partial $\eta^2 = 0.158$. The conditions × time windows interaction was also significant, $F(2,64) = 6.15$, $p = .004$, partial $\eta^2 = 0.161$ (Fig. 3). In addition, the main effect of sickness groups was significant, $F(1,32) = 4.65$, $p = .039$, partial $\eta^2 = 0.127$. Positional variability was greater in the sick group (mean = 29.73 cm, SD = 6.37 cm) than in the well group (mean = 14.17 cm, SD = 3.40 cm).

Temporal dynamics of the head

In the AP axis, the main effect of time windows was significant, $F(1,32) = 3.28$, $p = 0.044$, partial $\eta^2 = 0.093$ ($\text{mean}_{W1} = 1.042$, SD = 0.032 cm; $\text{mean}_{W2} = 1.079$, SD = 0.042; $\text{mean}_{W3} = 1.199$, SD = 0.058). In addition, the conditions × sickness groups interaction was significant, $F(1,32) = 4.27$, $p = .047$, partial $\eta^2 = 0.118$ (Fig. 4).

In the ML axis, there was a significant main effect of time windows, $F(2,64) = 4.13$, $p = .021$, partial $\eta^2 = 0.114$ ($\text{mean}_{W1} = 1.108$, SD = 0.066; $\text{mean}_{W2} = 1.157$, SD = 0.073; $\text{mean}_{W3} = 1.367$, SD = 0.081). The main effect of conditions was significant, $F(1,32) = 4.57$, $p = 0.04$, partial $\eta^2 = 0.125$ ($\text{mean}_{\text{Touch}} = 1.314$, SD = 0.081; $\text{mean}_{\text{Tilt}} = 1.108$, SD = 0.051). In addition, the main effect of sickness groups was significant, $F(1,32) = 6.04$, $p = .02$, partial $\eta^2 = 0.159$ ($\text{mean}_{\text{Well}} = 1.092$, SD = 0.074; $\text{mean}_{\text{Sick}} = 1.329$, SD = 0.091).

Positional variability of the torso

In the AP axis, the main effect of time windows was significant, $F(2,64) = 3.72$, $p = .030$, partial $\eta^2 = 0.104$. Positional variability exhibited a U-shaped function ($\text{Mean}_{W1} = 1.40$ cm, SD = 0.17 cm; $\text{Mean}_{W2} = 1.06$ cm, SD = 0.18 cm; $\text{Mean}_{W3} = 1.97$ cm, SD = 0.44 cm). The main effect of sickness groups was also significant, $F(1,32) = 4.23$, $p = .048$, partial $\eta^2 = 0.117$. Positional variability for the sick group (mean = 1.92 cm, SD = 0.38 cm) was greater than for the well group (mean = 1.04 cm, SD = 0.20 cm). In the ML axis, there were no significant effects.

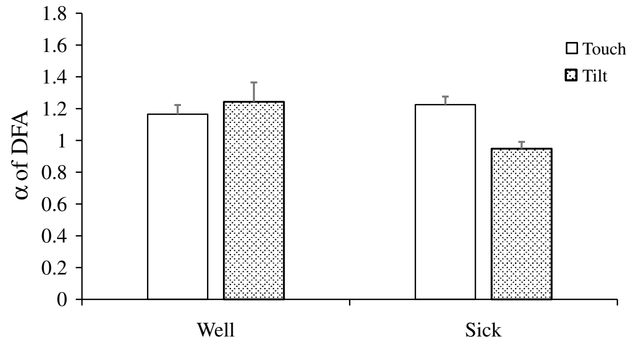

Fig. 5 Statistically significant interaction between sickness groups (well vs. sick) and conditions (touch vs. tilt) for DFA for movement of the torso in the AP axis. The *error bars* represent standard error of the mean

Temporal dynamics of the torso

In the AP axis, the conditions × sickness groups interaction was significant, $F(1,32) = 5.34$, $p = .027$, partial $\eta^2 = 0.143$ (Fig. 5). In the ML axis, there were no significant effects.

Discussion

Participants played a video game on a tablet computer. In the Touch condition, the device was mounted on a stationary stand and participants used only finger movements to control the game. In the Tilt Condition, participants held the device and used hand movements to control motion of the game avatar. Motion sickness occurred in both conditions, confirming anecdotal reports that tablet computers can give rise to motion sickness. The incidence of motion sickness was greater in the Touch condition, indicating that motion sickness incidence was related to the nature of control that participants exercised over the game. During game play, movements of the head and torso differed between the Touch and Tilt conditions and between players who later reported motion sickness and those who did not. Finally, patterns of movement in Well and Sick players differed with the nature of control. We discuss these results in turn.

Motion sickness and tablet computers

Anecdotal reports have suggested that contemporary mobile devices, including tablet computers, can give rise to motion sickness among users (e.g., Daily Mail 2013). Our results provide the first controlled, experimental confirmation of those anecdotal reports for the case of tablet computers. The overall incidence of motion sickness (31 %) was comparable with incidence rates observed among players of console video games (e.g., Chen et al. 2012; Dong et al. 2011; Stoffregen et al. 2008).

Game control and motion sickness incidence

The incidence of motion sickness was powerfully influenced by the nature of control that participants exerted over the game: Motion sickness among participants in the Touch condition was nearly five times more common than among participants in the Tilt condition. Dong et al. (2011) exposed participants to a driving video game. Some participants controlled the game (i.e., they drove the virtual car), while others simply watched pre-recorded game play. Fifteen percent of drivers reported motion sickness. By contrast, motion sickness was reported by 69 % of participants who watched pre-recorded game play. Chen et al. (2012) exposed participants to a video game featuring virtual ambulation (an avatar that walked through a virtual environment). Some participants controlled the avatar (players), while others simply watched pre-recorded game play (viewers). Motion sickness was reported by 22 % of players, but by 56 % of viewers. In terms of motion sickness incidence, the results of Chen et al. and Dong et al. are comparable with the results of the present study despite the fact that, in the present study, all participants controlled all game functions. We conclude that motion sickness incidence can be affected by the type of control that people exercise over stimulus motion and that this effect can be as large as the difference between drivers and passengers.

Our results suggest that the traditional dichotomous view of motion control that has been adopted in theoretical discussions of motion sickness etiology (e.g., Oman 1982; Reason 1978; Rolnick and Lubow 1991) may be inadequate (cf. Stanney and Hash 1998). Our results motivate theorists to consider ways in which the control of motion stimuli can differ across situations and how these may affect the etiology of motion sickness. The Touch and Tilt conditions did not differ in the "amount" of control that participants exerted: Participants controlled the same game functions in both conditions. Rather, the conditions differed in the way in which control was exerted.

The sensory conflict theory predicts that individual differences in motion sickness incidence should be related to individual differences in the magnitude of hypothetical conflict between current and expected patterns of multisensory stimulation. Thus, the theory would seem to mandate a claim that the touch condition led to greater intersensory conflict than the tilt condition. Such a claim might be plausible if people typically choose to use tilt control. Then, it might be argued that pre-existing expectations would be met more often in the Tilt condition due to its greater familiarity. However, this argument would predict an effect of game experience on sickness, and we did not find such an effect. For this reason, it is not clear how the effect of conditions on the incidence of motion sickness might be interpreted within the sensory conflict theory of motion sickness. An interpretation from the perspective of postural instability theory is presented in a later section.

Game performance and motion sickness

Participants who later reported motion sickness died more often (that is, their game avatars died more often) than participants who did not report motion sickness. This difference in game performance existed before the onset of subjective symptoms of motion sickness, that is, the level of game performance was related to the likelihood that game play would lead to motion sickness. It may be that incipient sickness impeded performance. This seems unlikely, given our explicit, repeated instructions to discontinue game play immediately at the onset of any symptoms, however, mild. An alternative interpretation is that unstable control of the head and torso contributed to poor performance in the game (cf. Chen et al. 2013). Participants who were less able to stabilize their gaze relative to the game display may have had greater difficulty in seeing the game (e.g., noticing or identifying threats to the avatar), or in responding to such threats (e.g., visually guided aiming of weapons).

Game control and body movement

Movement of the head and torso differed between participants as a function of the type of control that they exerted over the game. Some of these effects were independent of whether or not individual participants reported motion sickness. Effects of this kind were found only for movement of the head, and only in the ML axis (Fig. 3). Head ML was more self-similar in Touch than in Tilt. The effects are complex; it was not the case that one condition simply moved more than the other.

These effects did not interact with sickness status; thus, they indicate differences relating to the type of control, per se. Previous studies have found differences in body movement between persons who controlled a potentially nauseogenic motion stimulus and those who did not. Dong et al. (2011) found that drivers moved more than passengers (greater positional variability) and that the movements of drivers were more predictable or self-similar than the movement of passengers. Chen et al. (2012) reported the same effects in the context of the control of virtual ambulation. Those effects are not directly comparable with Touch/Tilt effects, which, for this reason, appear to be novel effects.

Body movement and motion sickness

We found several main effects of sickness groups on movement of the head and torso. The Sick group moved more and moved with greater self-similarity, replicating previous studies with video games (e.g., Dong et al. 2011), with laboratory devices (e.g., Smart et al. 2002), and among passengers on a ship at sea (Stoffregen et al. 2013). In addition, sickness-related movement patterns evolved over time (Fig. 2), consistent with previous studies in a variety of settings (Dong et al. 2011; Faugloire et al. 2007; Stoffregen et al. 2008, 2010; Villard et al. 2008). These effects indicate that, regardless of the nature of control that participants exercised over the game, particular patterns of body movement preceded the onset of subjective symptoms of motion sickness.

We also found that the type of control that participants exerted over the game affected the nature of movement patterns that preceded motion sickness. Before the onset of subjective symptoms of motion sickness, the type of control that participants exerted over the game was associated with different patterns of head and torso movement as a function of subsequent membership in the Well and Sick groups (Figs. 4, 5). Condition-related differences in movement between Well and Sick participants were qualitative: In the Touch condition, movement was more self-similar among sick participants than among well participants, while in the Tilt condition, movement was more self-similar among sick participants than among well participants. These effects are novel. They provide direct evidence of a link between the control of the game, the control of the body, and subsequent motion sickness.

The finding that movement of the head and torso differed between participants who later reported motion sickness and those who did not and that these differences occurred before any participants reported motion sickness is compatible with the postural instability theory of motion sickness (Riccio and Stoffregen 1991).

Taken together, the effects on incidence, overall movement, and sick/well movement suggest an interpretation from the perspective of the postural instability theory of motion sickness. In the Touch condition, stabilization of gaze relative to the virtual environment was solely dependent upon movements of the body (eyes, head, torso). By contrast, in the Tilt condition, participants had the opportunity to stabilize gaze by coupling movements of the eyes, head, and/or torso with movements of the handheld device. For these reasons, stabilization of gaze relative to the virtual environment of the game may has been easier in the Tilt condition than in the Touch condition. To test this interpretation, it would be necessary to have data on movement of the eyes, head, torso, display device (e.g., the iPad) and display content (i.e., movement within the virtual world of the game).

Conclusion

In the present study, participants played a commercially available video game that was presented on a tablet computer. In the Touch condition, participants controlled all game functions using fingertip contact with the device's touch screen. In the Tilt condition, participants held the device in their hands and moved it to control locomotion of a virtual avatar (remaining game functions were controlled through fingertip contact). Motion sickness was more common in the Touch condition than in the Tilt condition, suggesting that the influence of motion control of motion sickness is more complex than is reflected in the classical observation that drivers are less likely to become motion sick than passengers. In addition, movement of the head and torso differed as a function of conditions and differed between participants who later reported motion sickness and those who did not. In a novel finding, differences in movement between Well and Sick participants differed qualitatively between the experimental conditions.

We collected data about performance, but we could not obtain data about how participants played the game. The ability to use hand and arm movements in the Tilt condition may have led to differences in game play that, in turn, could be related to movements of the body and to motion sickness. This possibility should be addressed through future research. It would also be interesting to obtain measures of the subjective magnitude of being in control in the Touch and Tilt conditions (e.g., Chambon and Haggard 2012) and to relate these to both postural activity and motion sickness.

Our results confirm anecdotal accounts that use of mobile, handheld devices can lead to motion sickness. Handheld devices are often used for video game play on moving vehicles, as when commuters play video games on smart phones or tablets while riding a bus or train to work. In some ways, this situation is comparable with the use of flight simulators as training devices for naval aviators on aircraft carriers. The results of the present study highlight the need for research investigating movement (and the stability of movement) when simulation devices are "embedded" within physical vehicles.

Our results have implications for general theories of motion sickness etiology. Such theories may need to be modified to accommodate the idea that control of stimulus motion is not a dichotomous variable. Specifically, theories should attempt to account for the differing nauseogenic properties of different types of stimulus motion control. In this respect, the present study exemplifies Greenwald's (2012) claim that the development of new research methods can motivate improvements in theoretical understanding.

References

Chambon V, Haggard P (2012) Sense of control depends on fluency of action selection, not motor performance. Cogni 125:441–451
Chang C-H, Pan W-W, Tseng L-Y, Stoffregen TA (2012) Postural activity and motion sickness during video game play in children and adults. Exp Brain Res 217:299–309
Chang C-H, Pan W-W, Chen F-C, Stoffregen TA (2013) Console video games, postural activity, and motion sickness during passive restraint. Exp Brain Res 229:235–242
Chen Z, Ivanov PC, Hu K, Stanley HE (2002) Effect of nonstationarities on detrended fluctuation analysis. Phys Rev E 65:041107
Chen Y-C, Dong X, Chen F-C, Stoffregen TA (2012) Control of a virtual avatar influences postural activity and motion sickness. Ecol Psych 24:279–299
Chen Y-C, Tseng T-C, Hung T-H, Hsieh CC, Chen F-C, Stoffregen TA (2013) Cognitive and postural precursors of motion sickness in adolescent boxers. Gait Pos 38:795–799
Cohen J (1988) Statistical power analysis for the behavioral sciences. Erlbaum, Hillsdale, NJ
Daily Mail Online (2013) The rise of digital motion sickness: video games, 3D films and iOS7 set to make condition the 21st century's biggest occupational disease. Daily Mail Online. http://www.dailymail.co.uk/sciencetech/article-2436638/Video-games-3D-films-iOS7-Why-digital-motion-sickness-tipped-21st-centurys-biggest-occupational-disease.html#ixzz2jE2n3uhP. Accessed 13 Nov 2013
Dong X, Yoshida K, Stoffregen TA (2011) Control of a virtual vehicle influences postural activity and motion sickness. J Exp Psych App 17:128–138
Draper MH, Viirre ES, Gawron VJ, Furness TA (2001) The effects of image scale and system delay on simulator sickness within head-coupled virtual environments. Hum Fac 43:129–146
Faugloire E, Bonnet CT, Riley MA, Bardy BG, Stoffregen TA (2007) Motion sickness, body movement, and claustrophobia during passive restraint. Exp Brain Res 177:520–532
Greenwald AG (2012) There is nothing so theoretical as a good method. Persp Psych Sci 7:99–108
Guignard JC, McCauley ME (1990) The acceleration stimulus for motion sickness. Motion and space sickness. CRC Press, Boca Raton, FL
Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG (1993) Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. Int J Aviat Psych 3:203–220
Lawther A, Griffin MJ (1986) The motion of a ship at sea and the consequent motion sickness amongst passengers. Ergon 29:535–552
Lin D, Seol H, Nussbaum MA, Madigan ML (2008) Reliability of COP-based postural sway measures and age-related differences. Gait Pos 28:337–342
Littman EM, Otten EW, Smart LJ (2010) Consequences of self versus externally generated visual motion on postural regulation. Ecol Psych 22:150–167
Merhi O, Faugloire E, Flanagan M, Stoffregen TA (2007) Motion sickness, console video games, and head mounted displays. Hum Fac 49:920–934
Oman CM (1982) A heuristic mathematical model for the dynamics of sensory conflict and motion sickness. Acta Otolaryngol 44(Suppl):392
Reason JT (1978) Motion sickness adaptation: a neural mismatch model. J R Soc Med 71:819–829
Riccio GE, Stoffregen TA (1991) An ecological theory of motion sickness and postural instability. Ecol Psych 3:195–240
Rolnick A, Lubow RE (1991) Why is the driver rarely motion sick? The role of controllability in motion sickness. Ergon 34:867–879
Smart LJ, Stoffregen TA, Bardy BG (2002) Visually-induced motion sickness predicted by postural instability. Hum Fac 44:451–465

Stanney K, Hash P (1998) Locus of user-initiated control in virtual environments: influence on cybersickness. Presence 7:447–459

Stanney K, Salvendy G, Deisinger J, DiZio P, Ellis S, Ellision J, Fogleman G, Gallimore J, Hettinger, L, Kennedy R, Lackner J, Lawson B, Maida J, Mead A, Mon-Williams M, Newman D, Piantanida T, Reeves L, Riedel O, Singer M, Stoffregen T, Wann J, Welch R, Wilson J, Witmer R (1998) Aftereffects and sense of presence in virtual environments: formulation of a research and development agenda. Report sponsored by the Life Sciences Division at NASA Headquarters. Int J Hum Comput Interact 10:135–187

Stoffregen TA, Faugloire E, Yoshida K, Flanagan M, Merhi O (2008) Motion sickness and postural sway in console video games. Hum Fac 50:322–331

Stoffregen TA, Yoshida K, Villard S, Scibora L, Bardy BG (2010) Stance width influences postural stability and motion sickness. Ecol Psych 22:169–191

Stoffregen TA, Chen F-C, Varlet M, Alcantara C, Bardy BG (2013) Getting your sea legs. PLOS ONE 8(6):e66949. doi:10.1371/journal.pone.0066949

Villard S, Flanagan MB, Albanese G, Stoffregen TA (2008) Postural instability and motion sickness in a virtual moving room. Hum Fac 50:332–345