Effects of Physical Driving Experience on Body Movement and Motion Sickness During Virtual Driving

Chih-Hui Chang; Fu-Chen Chen; Wei-Ching Kung; Thomas A. Stoffregen

BACKGROUND: In previous research on motion sickness in simulated and virtual vehicles, subjects' experience controlling the corresponding physical vehicles has been confounded with their age. During driving of virtual automobiles in a video game, we separated chronological age from experience driving physical automobiles.

METHODS: Subjects drove a virtual automobile in a driving video game. Drivers were young adults with several years of experience driving physical automobiles, while nondrivers were individuals in the same age group who did not have a driver's license and had never driven an automobile. During virtual driving, we monitored movement of the head and torso. We collected independent measures of the incidence and severity of motion sickness.

RESULTS: After virtual driving, motion sickness incidence did not differ between drivers (65%) and nondrivers (60%). Game performance and the severity of symptoms also did not differ between drivers and nondrivers. However, movement differed between subjects who later became motion sick and those who did not. In addition, physical driving experience influenced patterns of postural activity that preceded motion sickness during virtual driving.

CONCLUSIONS: The results are consistent with the postural instability theory of motion sickness, and help to illuminate relationships between the control of physical and virtual vehicles.

KEYWORDS: motion sickness, driving, postural control.

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Vehicle simulators are associated with the risk of motion sickness. Some researchers have argued that the risk of motion sickness in driving simulators increases with age.[3,14] By contrast, other researchers have argued that the risk of motion sickness in flight simulators is related to flying experience, rather than to chronological age.[8] In the present study, we asked how subjects' experience driving physical automobiles might influence behavior during the driving of virtual automobiles.

Several studies have reported that the severity of motion sickness in a flight simulator was positively correlated with the amount of time that subjects had spent flying the corresponding physical aircraft.[2,8,16] An important limitation of these studies is that pilot experience was confounded with chronological age: In each study, more experienced pilots were chronologically older, while less experienced pilots were chronologically younger. The same is true of research on driving simulators, in which older drivers had more extensive driving experience.[3,14] For automobiles, separation of driving experience from chronological age is difficult, due to the fact that in many countries essentially the entire adult population are drivers. However, there are countries in which substantial portions of the adult population do not have driver's licenses, and have never driven an automobile. In these countries, it is possible to separate chronological age from driving experience. One such country is Taiwan, where our study was conducted. For this reason, our study offers what may be the first attempt, under controlled laboratory conditions, to eliminate the confound between age and experience.

In physical driving, accelerations (including linear acceleration, such as speeding up and slowing down, and angular acceleration, such as turns) give rise to changes in visual and

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vestibular stimulation; i.e., occupants both see and feel accelerations. By operating the accelerator, brake, and steering wheel, drivers control the automobile's acceleration, and so they control these patterns of visual, haptic, and vestibular stimulation. Within the sensory conflict theory of motion sickness etiology,[17,18] experience driving physical automobiles is hypothesized to create internal expectations about relationships between visual, haptic, and vestibular stimulation during accelerations. These expectations will include the temporal sequence between feedback arising from control actions (pressing pedals, turning the wheel), and the resulting inertial forces that, in turn, alter multisensory stimulation.

Fixed-base virtual vehicles, including driving video games, do not reproduce the inertial forces that accompany physical driving and, therefore, do not reproduce relationships between the driver's control actions and patterns of multisensory stimulation that characterize driving in physical automobiles. For this reason, virtual driving should give rise to strong conflict between current patterns of intersensory input and patterns of expected input that are hypothesized to result from physical driving. People who have never driven a physical automobile should have no quantitative expectations about sensory feedback about their own actions in relation to patterns of intersensory stimulation during driving. Thus, during virtual driving, persons who have never driven a physical automobile should experience less intersensory conflict than persons who have driven physical automobiles. By this logic, the intersensory conflict theory would appear to mandate a prediction that—during virtual driving—motion sickness should be more common and/or more severe among persons with physical driving experience than among persons who have never driven a physical automobile.

We understand that everyone has extensive experience riding in physical automobiles, that is, as passengers. However, any expectations about patterns of intersensory stimulation arising from experience as a passenger should be irrelevant to situations in which the individual is the driver. That drivers and passengers must have very different (hypothetical) expectations about patterns of intersensory stimulation is demonstrated by the fact that—in the same vehicle—passengers are more likely to experience motion sickness than drivers, an effect that has been documented in physical vehicles,[20] and in virtual automobiles.[9] Given that the motion stimuli are the same (both driver and passenger are sitting in the same vehicle), the difference in motion sickness incidence between drivers and passengers cannot be explained in terms of motion stimulation. Within the sensory conflict theory, the only alternative option for explanation is in terms of the hypothetical internal expectations.[17]

Riccio and Stoffregen[19] offered an alternative theory of motion sickness etiology. They pointed out that intersensory conflict is hypothetical, rather than being a fact.[22,27] In addition, they argued that hypothetical internal expectations cannot be known by the scientist (e.g., cannot be quantified), due to their basis in physical experience outside the laboratory which, itself, cannot be known (in quantitative detail) by the scientist. This problem is especially clear in the context of driving. Patterns of intersensory stimulation that occur during driving of physical automobiles vary with traffic and road conditions (e.g., weather, terrain), with variation in routes traversed, with individual differences in driving style, and with characteristics of individual automobiles. For this reason, scientists can have no quantative data about hypothetical expectations about intersensory stimulation arising from experience driving physical automobiles. This fact, in turn, means that it is impossible for scientists to compute quantitatively the magnitude of hypothetical intersensory conflict between current patterns of intersensory input and those expected on the basis of past experience.[19] For this reason, the concept of intersensory conflict cannot be used to make quantitative predictions about motion sickness susceptibility in individuals.

Riccio and Stoffregen[19] argued that motion sickness arises from instability in the control of the body (the entire body, or its segments). The most direct prediction of this theory is that there should differences in movement between persons who experience motion sickness and those who do not, and that these differences should exist before the onset of any symptoms of motion sickness. This prediction has been confirmed in laboratory devices,[12,28,29] virtual environments,[30] fixed-base flight simulators,[26] video games,[4,9,15] and seasickness.[23]

As noted above, physical driving entails changes in forces acting on the body, while such changes are absent in fixed-base virtual vehicles. For this reason, physical and virtual automobiles impose different constraints on control of the body. In physical automobiles, occupants must actively adjust their bodies in response to forces associated with acceleration. In virtual automobiles, turns and accelerations have only visual consequences: They do not induce inertial motion, and for this reason drivers of virtual automobiles are not obliged to adjust their bodies in response to virtual accelerations. Physical driving experience may lead to patterns of body movement during accelerations that are related to the fact that drivers control the accelerations. Any such patterns would tend to differ qualitatively from patterns that might be learned from experience as a passenger, given that passengers are not in control of accelerations: for drivers, postural adjustments can be anticipatory, while for passengers they must be compensatory. For this reason, the postural instability theory of motion sickness predicts that patterns of body movement that precede motion sickness during virtual driving will differ between persons with and without physical driving experience.

We asked how prior experience of driving physical automobiles might affect body movement and motion sickness when driving a virtual automobile. We separated chronological age from the experience of driving physical automobiles. In Taiwan, the minimum age at which persons may obtain a driver's license is 18 yr. Among persons aged 18 and above, fewer than 70% actually hold a driver's license, thus making it relatively easy for us to recruit as subjects equal numbers of persons with and without experience driving physical vehicles. We asked whether motion sickness during driving of a virtual automobile would differ between subjects who had or did not have experience driving physical vehicles. During video game play, we predicted that drivers and nondrivers would move differently, and that postural instabilities would precede the onset of motion sickness. Finally, we predicted that patterns of body movement that preceded motion sickness would differ between persons with and without experience driving physical vehicles.

METHODS

There were 20 individuals (mean age = 24.08 ± 2.86 yr; mean height = 169.94 ± 9.85 cm; mean weight = 65.69 ± 13.38 kg; 10 men and 10 women) who were assigned to the driver group. Each driver held a current, valid driver's license. Among drivers, the mean age at which they obtained the driver's license was 19.30 yr (SD = 2.05 yr). Each driver reported that, over the preceding 2 mo, they had driven at least once each week and, on average, 3.3 days per week. Another 20 individuals (mean age = 23.83 ± 2.83 yr; mean height = 166.57 ± 8.20 cm; mean weight = 61.44 ± 9.93 kg; 10 men and 10 women) were assigned to the nondriver group. Nondrivers did not hold a driver's license and had never driven any automobile. Drivers had an average of 15.30 yr of education (SD = 1.38 yr), while for nondrivers the mean was 15.20 yr (SD = 1.99 yr); these means did not differ, $t(38) = 0.19$, $P = 0.85$. All subjects had normal or corrected-to-normal vision, and reported that they had no history of disease or malfunction of the vestibular apparatus, recurrent dizziness, or falls. Informed consent was obtained from the subjects. The experimental protocol was approved by the Research Ethics Committee for Human Behavioral Sciences of National Cheng Kung University.

The experiment was conducted using a standard Xbox system (Xbox 360 pro, Microsoft Corp.), which included the game unit, containing graphics and control software, and the game pad, a handheld device that subjects used to control the game. The video and audio portions of the game were presented using an LED monitor (KDL-55NX720, Sony) that measured 139.67 cm diagonally (122 cm × 68 cm). Subjects sat on a stool that did not support the torso.[9] The stool was 46 cm high. Subjects rested their feet on the floor and were asked not to change their foot position during the session. The stool had four feet; the front two feet were placed on the line on the floor 105 cm away from the monitor. The visual angle of the screen was approximately 60° horizontal by 36° vertical.

Data on head and torso movement were collected using a magnetic tracking system (Flock of Birds, Ascension Technologies, Inc., Burlington, VT). One receiver was attached to a bicycle helmet and another to the skin at the level of the 7th cervical vertebra using cloth medical tape. The transmitter was located behind each subject's head. Six degrees-of-freedom position data were collected from each receiver at 60 Hz and stored for later analysis.

We separately assessed the incidence of motion sickness and the severity of symptoms. We assessed the incidence of motion sickness using a forced-choice, yes/no question: "Are you motion sick?" Subjects who answered "yes" were assigned to the sick group; all others were assigned to the well group. We assessed symptom severity using a modified version of the Simulator Sickness Questionnaire (SSQ),[11] which includes 16 items with a 4-point scale. The modification consisted of the inclusion of our forced-choice question about motion sickness incidence. The questions were translated into Chinese. The SSQ was completed twice, as described below.

After completing the informed consent procedure, subjects filled out the SSQ. The pre-exposure administration ensured that subjects were not already motion sick, that they were familiar with the subjective symptoms of motion sickness, and it also provided a baseline for comparison with postexposure scores.

Next, subjects were given a brief introduction to the Xbox system and to the game and were then permitted to explore the game until they felt that they understood the rules and the use of the game pad. Subjects played *Forza Motosport 3*, an auto racing game, using the game pad. Subjects freely controlled both speed and steering. Positive acceleration (speeding up) was achieved with a button controlled by the right index finger, while negative acceleration (braking) was achieved via a button controlled by the left index finger. The left thumb operated a directional button that was used to control the right or left direction of the car. Subjects drove the Ford/R3 714 over a 6.95 km Extreme Circuit in the Camino Viejo de Montserrant (**Fig. 1**). The course traversed mountainous terrain, requiring frequent acceleration and braking. The camera/viewpoint was set at the driver's seat, a first-person perspective. We used the default setting, in which the handheld controller briefly vibrated if the virtual vehicle came into (virtual) contact with other virtual vehicles, walls, or obstacles, or if it left the virtual road. Subjects were instructed to complete the designated course as quickly as possible. Subjects played the game continuously for up to 40 min. Data on head and torso movement were collected continuously from the beginning to the end of game play (i.e., until the end of the 40-min session, or until the subject discontinued participation, whichever came first).

Once the game ended, subjects' game performance, including time elapsed in the present lap, the number of laps completed, and their fastest lap, was shown on the screen. At the end of 40 min (or at the time of discontinuation, whichever came first) subjects completed the postexposure SSQ.

Before beginning game play, subjects were told that if they felt any symptoms of motion sickness, no matter how slight, they should stop playing immediately.[9] For this reason, all movement data included in our analyses were precursors to subjective symptoms of motion sickness.[4,9,12]

We included all subjects in our analyses of game performance, motion sickness incidence, discontinuation, and symptom severity. We used χ^2 statistics to analyze the data on motion sickness incidence. In evaluating SSQ data, we used the Total Severity Score, which was computed in the recommended manner.[11] SSQ data were evaluated using the Mann-Whitney test and the Wilcoxon signed ranks test. We evaluated game performance in two ways. First, we computed the percent of subjects who completed at least one lap. Second, we recorded

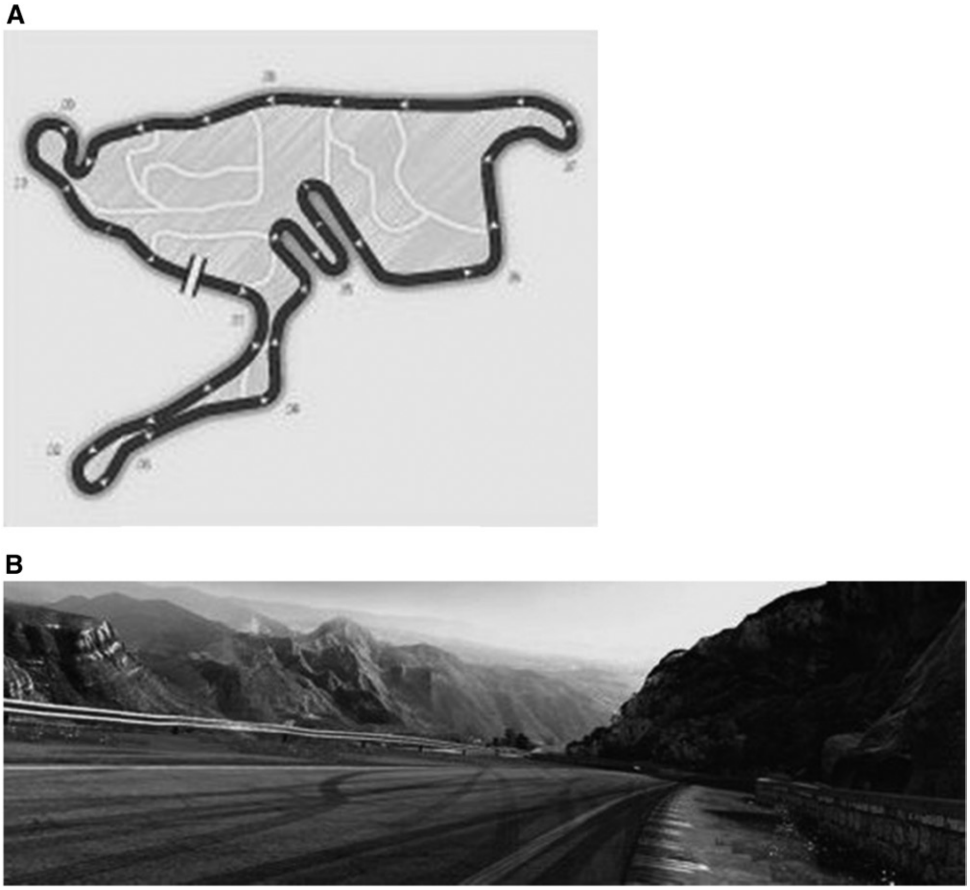

Fig. 1. The driving game. A. Overhead representation of the course (circuit). B. Momentary driver's-eye view.

the duration of the fastest lap. We used χ^2 statistics and the Mann-Whitney test to analyze these performance data.

We separately evaluated the spatial magnitude of movement and its temporal dynamics. For each of these measures, we conducted separate analyses for movement in the anteroposterior (AP) and mediolateral (ML) axes of the head and torso. We evaluated the spatial magnitude of movement in terms of the standard deviation of position of the head and torso. We evaluated the temporal dynamics of movement in terms of α, the scaling exponent of value of detrended fluctuation analysis (DFA). DFA describes the relationship between the magnitude of fluctuations in postural motion and the time scale over which those fluctuations are measured.[6] The scaling exponent of DFA, α, 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. DFA has been widely used to evaluate the temporal dynamics of human movement in terms of standing body sway,[13] and in relation to visually induced motion sickness.[12,29,30]

In our ANOVAs, we estimated the effect size using the partial η^2 statistic. According to Cohen,[7] values of partial $\eta^2 > 0.14$ indicate a large effect, and values of partial $\eta^2 > 0.06$ indicate a medium effect. When the sphericity assumption was violated, we used the Huynh-Feldt method.[10] The Huynh-Feldt method yields fractional degrees of freedom, which we report where appropriate.

RESULTS

We classified subjects into Well and Sick groups based solely on their responses to the forced-choice, yes/no question: "Are you motion sick?" Prior to virtual driving, each subject stated that they were not motion sick. After virtual driving, the overall incidence of motion sickness was 62.5% (25/40). There were 13 drivers (65%) who stated that they were motion sick, including 6 men and 7 women; 12 nondrivers (60%) stated that they were motion sick, including 6 men and 6 women. Using a 2 × 2 contingency table, the percentage of drivers and nondrivers reporting motion sickness did not differ, χ^2 (1) = 0.11, P = 0.74. Motion sickness incidence also did not differ between men (60%) and women (65%), χ^2 (1) = 0.11, P = 0.74.

Each subject in the well group completed the game session. Among drivers seven discontinued, each stating that they were motion sick. For these seven subjects, the mean time of discontinuation was 21.79 ± 13.55 min. Five drivers stated that they were motion sick after completing the 40-min game session. One driver who stated that he was not motion sick immediately after completing the 40-min game session stated that he became motion sick less than 1 h after leaving the laboratory. Therefore, among drivers who reported motion sickness the overall mean exposure time to the video game was 30.20 ± 13.46 min.

Among nondrivers, 10 discontinued, each stating that they were motion sick, with a mean time of discontinuation of 15.77 ± 11.62 min. Two nondrivers stated that they were motion sick after completing the 40-min game session. Therefore, among nondrivers who reported motion sickness the overall mean exposure time to the video game was 19.82 ± 14.15 min. The overall mean exposure times did not differ between drivers and nondrivers, $t(23) = 1.879$, $P > 0.05$.

The percentage of subjects who completed at least one lap did not differ between sick drivers (92.31%) and well drivers (100%), χ^2 (1) = 0.57, $P > 0.05$, or between sick nondrivers (91.67%) and well nondrivers (100%), χ^2 (1) = 0.70, $P > 0.05$. Among those who finished at least one lap, the fastest lap in minutes did not differ between the sick drivers (4.12 ± 1.71 min) and well drivers (3.28 ± 0.27 min), U = 23.00, or for sick nondrivers (4.57 ± 1.92 min) and well nondrivers (3.43 ± 0.75 min), U = 28.00, $P > 0.05$. The fastest lap in minutes did not differ between drivers and nondrivers for the sick group (mean sick drivers = 4.12 ± 1.71 min; mean sick nondrivers = 4.57 ± 1.92 min), $U = 62.00$, or for the well group (mean well drivers = 3.28 ± 0.27 min; mean well nondrivers = 3.43 ± 0.75 min), $U = 25.50$, $P > 0.05$.

Data on symptom severity are summarized in **Fig. 2**. At pre-exposure, SSQ scores did not differ between the sick and well groups for drivers, $U = 36.50$, $P > 0.05$, or for nondrivers, $U = 41.00$, $P > 0.05$. These results confirm that before driving the virtual automobile the groups did not differ in symptom severity.

Among sick drivers, postexposure scores were higher than pre-exposure scores, $Z = -3.18$, $P = 0.001$. Among well drivers, SSQ scores did not differ between postexposure and pre-exposure, $Z = -1.81$, $P > 0.05$. Among drivers, postexposure SSQ scores were greater for the sick group than for the well group, $U = 3.00$, $P < 0.001$. These results confirm that, for drivers, motion sickness was associated with an increase in symptoms.

Among sick nondrivers, postexposure scores were higher than pre-exposure scores, $Z = -2.99$, $P = 0.003$. Among well nondrivers, postexposure scores were also higher than pre-exposure scores, $Z = -2.03$, $P = 0.042$. Among nondrivers, postexposure SSQ scores were greater for the sick group than for the well group, $U = 6.50$, $P < 0.001$. These results indicate that control of the virtual vehicle increased symptom severity among all nondrivers, but that the increase was greater among nondrivers who stated they were motion sick.

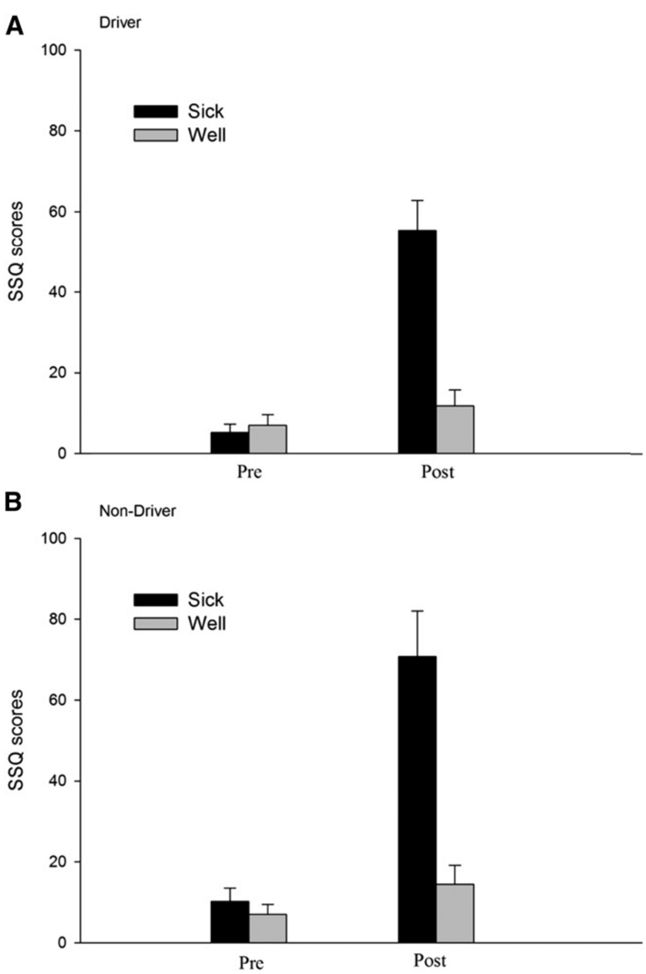

Fig. 2. Symptom severity (SSQ Total Severity Scores) for the Well and Sick groups. Pre: Pre-exposure. Post: Post-exposure. A. Drivers. B. Non-Drivers.

Postexposure SSQ scores did not differ between sick drivers and sick nondrivers, $U = 59.00$, $P > 0.05$. Postexposure SSQ scores also did not differ between well drivers and well nondrivers, $U = 23.50$, $P > 0.05$ ($P = 0.613$). Collapsed across sickness groups, postexposure SSQ scores did not differ between drivers and nondrivers, $U = 183.50$, $P > 0.05$. These results indicate that the possession of a driver's license did not influence the severity of postexposure symptoms.

We analyzed data on head and torso movement using a windowing procedure that permitted us to examine the evolution of movement over time during exposure to the video game.[9,15,25] We examined three nonoverlapping time windows (each 2 min in duration) selected from the beginning, middle, and end of the exposure. For this reason, we could include in our analysis only subjects who were exposed to the game for 6 min or more. One driver reported motion sickness at less than 6 min, and so was excluded from movement analysis.

We sought to compare the movement of well and sick subjects at equivalent times, that is, after equivalent exposure to the game. To do this, for the Well groups we defined the time windows in terms of the mean exposure times for subjects who reported motion sickness. To be conservative we used the shortest exposure time, that is, the mean exposure time from the sick nondriver group. Accordingly, for Well subjects, Window 1 comprised the first 120 s of game play, Window 2 ran from 8.91 to 10.91 min, and Window 3 ran from 17.82 min to 19.82 min. For each subject in the Sick group, the windows were defined as the first, middle, and final 2 min of data for that individual.

We conducted separate analyses of variance for head and torso movements in the AP and ML axes, using 2 (Sickness Groups: Well vs. Sick) × 2 (Driving Experience: Drivers vs. Nondrivers) × 3 (Time Windows: W1, W2, W3) ANOVAs with the last factor as the repeated measure. For movement magnitude, we analyzed the positional variability of the head and torso. For movement dynamics, the dependent variable was α, the scaling exponent of DFA, computed separately for the head and torso.

For movement in the AP axis, our analysis of positional variability yielded no significant effects. For head movement in the ML axis, the Sickness Groups × Time Windows interaction was significant, $F(2, 70) = 3.95$, $P = 0.02$, partial $\eta^2 = 0.10$ (**Fig. 3A**). For torso movement in the ML axis, the Sickness Groups × Time Windows interaction was also significant, $F(1.92, 67.24) = 3.88$, $P = 0.027$, partial $\eta^2 = 0.10$ (**Fig. 3B**). In addition, for the torso the Sickness Groups × Driving Experience interaction was significant, $F(1, 35) = 5.16$, $P = 0.029$, partial $\eta^2 = 0.13$ (**Fig. 4A**). Among nondrivers, the sick group showed larger positional variability than did the well group, while the trend was reversed for the drivers, with the well groups exhibiting larger positional variability than the sick group.

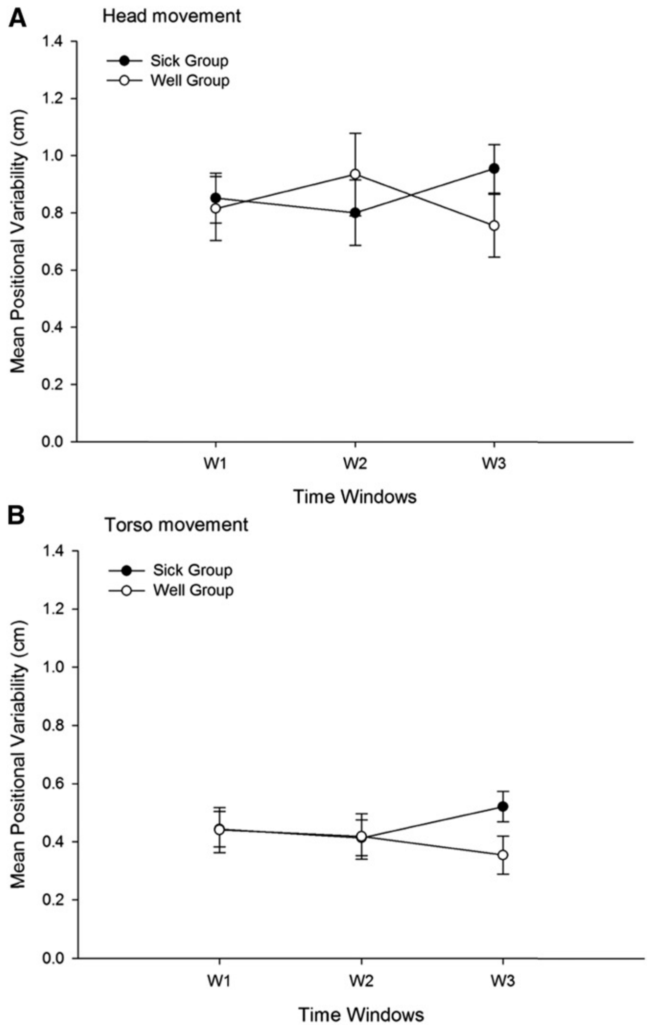

Fig. 3. Positional variability in the ML axis, illustrating statistically significant interactions between Sickness Groups and Time Windows. A. Head movement. B. Torso movement.

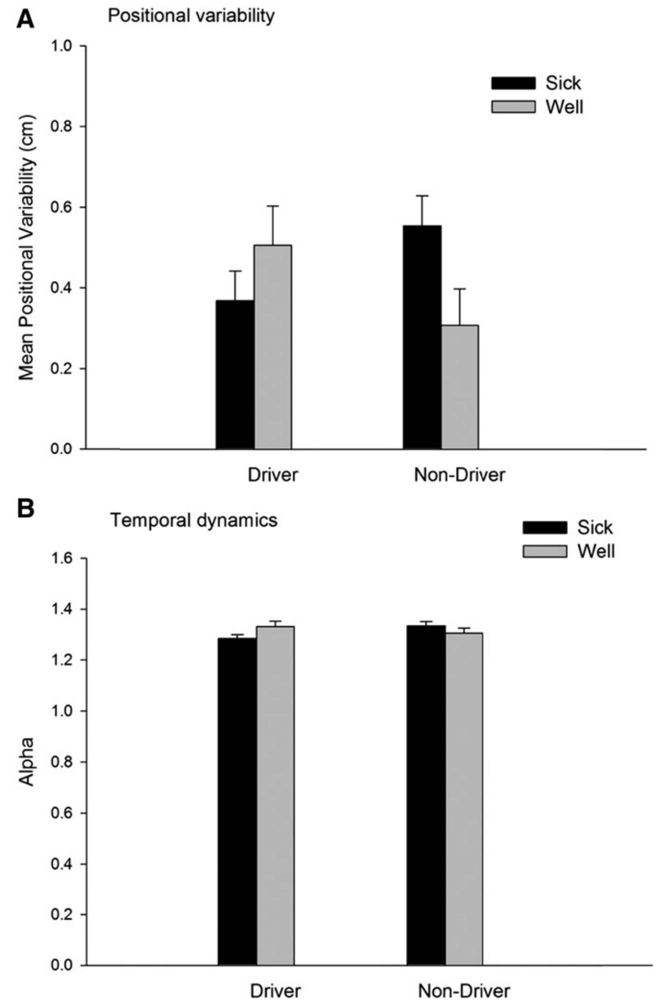

Fig. 4. Movement of the torso in the ML axis, illustrating statistically significant interactions between Driving Experience and Sickness Groups. A. Positional variability. B. Temporal dynamics (α of DFA).

There were no significant effects on the temporal dynamics of head movement in the AP or ML axes, or for movement of the torso in the AP axis. For torso movement in the ML axis, the Sickness Groups × Driving Experience interaction was significant, $F(1, 35) = 4.54$, $P = 0.04$, partial $\eta^2 = 0.12$ (**Fig. 4B**). Among nondrivers, the sick group had greater predictability or self-similarity in movement as compared to the well group, while the pattern was reversed for the drivers, with the well groups exhibiting greater predictability or self-similarity in movement than the sick group.

DISCUSSION

Young adults drove a virtual automobile in a driving video game. Half of the subjects held a driver's license and regularly drove physical automobiles. The other half of subjects did not hold a driver's license, and had never driven a physical automobile. During virtual driving, some subjects became motion sick, but the incidence of motion sickness did not differ between drivers and nondrivers. Drivers and nondrivers also did not differ in game performance, or in the severity of symptoms that are associated with motion sickness. By contrast, during virtual driving the kinematics of both head and torso movement differed between subjects who later reported motion sickness and those who did not, as a function of time during virtual driving. Finally, both in terms of spatial magnitude and temporal dynamics, patterns of movement that preceded motion sickness differed between drivers and nondrivers. We discuss these results in turn.

The incidence of motion sickness did not differ between the drivers and nondrivers. That is, among our young adult subjects, previous experience operating physical automobiles had no effect on the incidence of motion sickness during virtual driving. Pre-exposure symptom severity did not differ between the sick and well groups, but at postexposure the sick group exhibited more severe symptoms than did the well group. This was true for both drivers and nondrivers. We found no evidence that susceptibility to motion sickness was related to subjects' performance in the virtual driving task.

As noted in the Introduction, the intersensory conflict theory of motion sickness would argue that experience driving physical automobiles would give rise to expectations about intersensory stimulation that would be violated when driving virtual vehicles. Persons who had never driven physical vehicles would have no quantitative internalized expectations about driving. Accordingly, the intersensory conflict theory would appear to mandate a prediction that the risk of motion sickness while driving virtual automobiles would be greater for persons with a past history driving physical automobiles than for persons without such experience. Our results provided no support for this prediction.

The spatial magnitude of both head and torso movements differed between subjects in the well and sick groups as a function of time (Fig. 3). These interactions confirm our prediction that movement would differ between well and sick groups before the onset of subjective symptoms of motion sickness, and replicate previous studies.[1,9,30]

In addition, in statistically significant interactions both the spatial magnitude and the temporal dynamics of movement differed between the well and sick groups as a function of driving experience. As shown in Fig. 4, the differences in movement between well and sick drivers differed qualitatively from the differences in movement between well and sick nondrivers. These effects confirm our prediction that movement would differ between well and sick groups before the onset of subjective symptoms of motion sickness. However, in addition, the effects illustrated in Fig. 4 confirm our prediction that the experience of controlling physical automobiles influenced postural responses to the virtual vehicle, and that this effect was itself related to subsequent motion sickness. These effects are novel, and are the principal result of the study. Even among young adults, who had been driving for only a few years, the experience of operating a physical automobile changed the way that subjects controlled their bodies while driving a virtual automobile, and these changes were related to the risk of motion sickness in individuals. These results may be related to previous studies that have reported interactions between motion sickness status and the control of virtual vehicles (driver vs. passenger),[9] the control of virtual ambulation,[5] and/or the control of different aspects of virtual ambulation in video games played on a handheld mobile device.[24]

It would be interesting, in future research, to compare drivers and nondrivers for motion sickness in virtual vehicles in which all subjects are passengers (i.e., they watch the virtual vehicle, rather than control it).[9]

It is well known that, for persons riding in the same vehicle, those in control of the vehicle (i.e., drivers) are less likely to experience motion sickness than those not in control (i.e., passengers).[20] Recent research has demonstrated that these control-related variations in susceptibility are related to (and preceded by) patterns of body movement that differ between drivers and passengers.[5,9,24]

It is important to emphasize, again, that all of our subjects had extensive experience traveling in physical automobiles. Thus, the differences in movement that we observed between drivers and nondrivers cannot be attributed to "experience in physical automobiles," but must be attributed to the act of controlling physical automobiles. Our results show that the control of physical automobiles affected the quantitative kinematics of the body during the control of a virtual automobile.

Intersensory conflict has been offered as an explanation of the fact that drivers are less likely to experience motion sickness than passengers. In a given vehicle, drivers and passengers experience identical vehicular motion. Accordingly, the difference in motion sickness between drivers and passengers cannot be explained in terms of the motion stimulus, but can be explained only in terms of some difference arising from the act of controlling the vehicle. Drivers typically hold the driver's license for many years, and log many hours of actual driving. If driving leads to the creation of internal expectations about intersensory relations (during driving), these expectations should differ from expectations created in people who ride in automobiles but have never controlled them (that is, persons without a driver's license). Motion sickness sometimes occurs among adult passengers of physical automobiles. Within the theory of intersensory conflict, this sickness must be interpreted as arising from conflict between current stimulation and stored expectations.

In a novel effect, we found that patterns of body movement that preceded motion sickness differed between subjects who had driven physical automobiles and those who had not (Fig. 4). These statistically significant interactions reveal that driving of physical automobiles influences the quantitative kinematics of postural activity, that these effects are related to motion sickness susceptibility, and that they generalize beyond the act of physical driving; in this case, they were measurable during virtual driving. These effects on movement precursors of motion sickness were independent of effects of hypothetical expectations about intersensory stimulation on motion sickness, given that we found no evidence that either the incidence or severity of motion sickness differed between drivers and nondrivers. That is, driving experience altered the control of body movement in ways that were related to susceptibility to motion sickness in virtual driving. Accordingly, in our study the control of bodily movement (and its relation to motion sickness) appeared to be independent of any effects of hypothetical expectations on motion sickness. This pattern of results poses a challenge for theories of motion sickness etiology based on the concept of intersensory conflict. Control of body movement (i.e., the quantitative kinematics of the head and torso) appears to have been independent of hypothetical intersensory expectations. That is, hypothetical intersensory expectations do not appear to have been involved in the control of the body. Riccio and Stoffregen[19] argued that effects of this kind raise questions about the parsimony of the intersensory conflict theory: conflict (if it exists) appears to have the generation of motion sickness as its sole function.

Some studies suggest that persons of Asian descent have hypersensitivity to motion sickness.[21] An important limitation of these studies is that they have used only one type of stimulus motion in inducing motion sickness. Published research has relied upon passive viewing of the interior of a rotating drum (known as circular vection). It is not known whether ethnic differences extend to situations in which the motion stimulus is under the control of the subject. Consequently, we are not aware of any evidence to support the hypothesis that either the postural or motion sickness responses of drivers and passengers would differ as a function of ethnic origin.

It is widely believed that experience controlling physical vehicles influences the risk of motion sickness when controlling a virtual vehicle. However, in existing research, control experience has been confounded with age.[3] We separated subjects' experience driving physical automobiles from their chronological age in the context of virtual driving. We found no evidence that previous experience of driving a physical automobile influenced the incidence of motion sickness while driving a virtual automobile. The results are consistent with the postural instability theory of motion sickness, and help to illuminate relations between the control of physical and virtual vehicles. The principal limitation of our study was that we included only young adults. In future studies, it will be important to compare persons with and without driving experience in older age groups.

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