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Control of a virtual vehicle influences postural activity and motion sickness in pre-adolescent children

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ABSTRACT

Among adults, persons in control of a vehicle (i.e., drivers) are less likely to experience motion sickness compared to persons in the same vehicle who do not control it (i.e., passengers). This "driver-passenger effect" is well-known in adults, but has not been evaluated in children. Using a yoked-control design with seated pre-adolescent children, we exposed dyads to a driving video game. In each dyad, one child (the driver) drove the virtual vehicle. Their performance was recorded, and later shown to the other child (the passenger). Thus, visual motion stimuli were identical for the members of each dyad. During exposure to the video game, we monitored the quantitative kinematics of head and torso movements. Participants were instructed to discontinue participation immediately if they experienced any symptoms of motion sickness, however mild. Accordingly, the movements that we recorded preceded the onset of motion sickness. Results revealed that Passengers (73.08%) were more likely than Drivers (42.31%) to state that they were motion sick. Drivers tended to move more than passengers, and with a greater degree of multifractality. The magnitude of movement was greater among participants who later reported motion sickness than among those who did not. In addition, for the multifractality of movement a statistically significant interaction revealed that postural precursors of motion sickness differed qualitatively between Drivers and Passengers. Overall, the results reveal that control of a virtual vehicle reduces the risk of motion sickness among pre-adolescent children.

1. Introduction

A common anecdotal report is that persons who are in control of a vehicle, such as drivers, are less likely to become motion sick compared to 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. This "driver-passenger" effect has been documented in physical vehicles (Rolnick & Lubow, 1991), and in virtual vehicles (Dong, Yoshida, & Stoffregen, 2011). A similar effect occurs with respect to control versus passive observation of virtual ambulation (Chen, Dong, Chen, & Stoffregen, 2012).

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1.1. The driver-passenger effect among pre-adolescent children

Motion sickness occurs across the lifespan, from infants to the elderly (e.g., Huppert, Grill, & Brandt, 2019; Keshavarz, Novak, Hettinger, Stoffregen, & Campos, 2017). However, while motion sickness can occur at almost any age, the control of physical vehicles is restricted to adults. In most countries, law mandates that persons under some criterion age (usually 16–21 years) may not drive motor vehicles. In previous research on the driver-passenger effect, participants have been adults, and have been experienced drivers (e.g., Dong et al., 2011; Rolnick & Lubow, 1991). Research with adults has revealed that postural and subjective responses to virtual vehicles differ substantially depending upon participants' prior experience driving physical automobiles (Chang, Chen, Kung, & Stoffregen, 2017; Stoffregen, Chang, Chen, & Zeng, 2017). Pre-adolescent children generally have never driven a motor vehicle. Therefore, effects of prior driving experience that have been observed in adults cannot exist in pre-adolescent children. In this sense, child and adult populations differ qualitatively, so that research on the driver-passenger effect in pre-adolescent children is not a trivial extension of existing research with adults. In the present study, we asked whether the driver-passenger effect that has been observed in adults might occur among pre-adolescent children, in the context of virtual vehicles.

1.2. Sex differences and the driver-passenger effect

In many situations, motion sickness is characterized by sex differences, with females being more likely than males to suffer from the malady (e.g., Golding, 2006; Lawther & Griffin, 1988). Yet, little is known about how the driver-passenger effect may be related to sex differences. Rolnick and Lubow (1991) included only males in their sample. Dong et al. (2011) included women and men but did not analyze the data for possible sex differences. Curry, Li, Peterson, and Stoffregen (2020) investigated possible relations between sex differences and the driver-passenger effect in the context of head-mounted displays. They found a typical overall incidence of motion sickness, but with no evidence of any sex difference in incidence among drivers, or among passengers. In the present study, we asked whether there might be sex differences in the driver-passenger effect in pre-adolescent children exposed to a console video game.

1.3. The present study

Following previous studies, we used a yoked-control design (Dong et al., 2011; Rolnick & Lubow, 1991), 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).

2. Method

2.1. Participants

A total of 58 individuals participated. Twenty-nine Driver-Passenger dyads were recruited. Three of these dyads were excluded due to technical errors, leaving a total of 52 participants in our analysis. Among these 52 participants, for Drivers there were 13 females and 13 males, age = 9.50 ± 0.52 yrs.; height = 136.09 ± 9.73 cm; weight = 37.64 ± 14.34 kg), and for Passengers there were 13 females, and 13 males, age = 9.35 ± 0.81 yrs.; height = 136.11 ± 8.63 cm; weight = 33.07 ± 7.96 kg. All participants had normal or corrected-to-normal vision, and no self-reported history of disease or malfunction of the vestibular apparatus, recurrent dizziness, or falls. Informed consent was obtained from the parents of the participants. The experimental protocol and ethical aspects of the study were approved by the Institute of Review Board of National Kaohsiung Normal University.

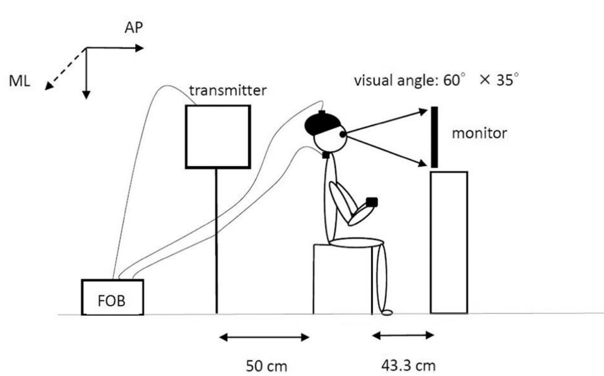

Fig. 1. Experimental setup.

2.2. Apparatus

The experimental setup illustrated is shown in Fig. 1. The experiment was conducted using a standard Xbox system (Xbox 360 pro system, Microsoft Corp), which included the game unit, the game pad, and a handheld device that participants used to play the game. The video and audio portions of the game were presented using an LCD monitor (KLT-321, Kolin) that measured 80 cm diagonally (70 cm × 39.5 cm). Participants sat on a stool, such that they were obliged actively to stabilize the torso and head. The stool's four feet formed a base of 40 cm × 40 cm; the front two feet were placed on a line 43.3 cm away from the monitor. The visual angle of the screen was approximately 60° horizontal by 35° vertical. Participants rested their feet on the floor and were asked not to change their foot position during the session.

Movement data were collected using a magnetic tracking system (Flock of Birds, Ascension Technologies, Inc., Burlington, VT). The system comprises a transmitter and several sensors. The transmitter creates a magnetic field, and the system detects the position of each sensor within the magnetic field. The magnetic field is centered on the transmitter, which serves as the 0 point for measurements. One receiver was attached to the apex of 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 participant's head, on a stand 50 cm from the two rear feet of the stool. Six-degrees-of-freedom position data were collected from each receiver at 40 Hz and stored for later analysis.

2.3. Procedure

We used a between-participants, yoked control design with individual Passengers being yoked to individual Drivers. Dyads were sex matched; that is, each dyad comprised two boys, or two girls. Within this constraint, odd-numbered participants were assigned to the Driver group, and even-numbered participants 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. Each person participated in only one condition.

Only one person participated at a time. After completing the informed consent procedure, participants filled out the pre-exposure Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Berbaum, & Lilienthal, 1993). The pre-exposure administration ensured that participants were familiar with the subjective symptoms of motion sickness and provided a baseline for comparison with post-exposure scores.

Drivers were given a brief introduction to the Xbox system and to the game. They practiced controlling the device for 3 min. Within this practice session, Drivers were free to ask questions about the game or the controls. Passengers watched a three-minute practice session prerecorded by the Experimenter. Before being exposed to the game, participants were told that if they felt any symptoms of motion sickness, no matter how slight, they should stop playing immediately.

Drivers played *Forza Motosport 3*, a car racing game, using the game pad. 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

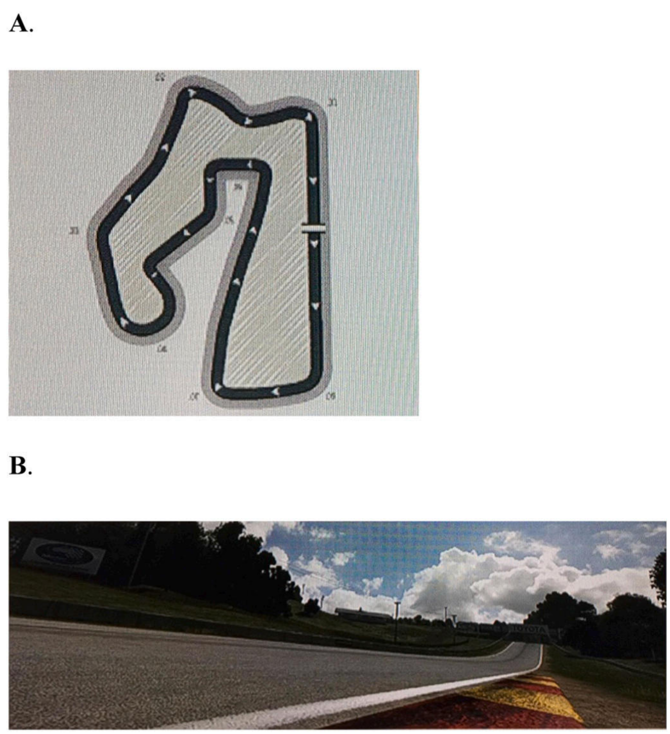

Fig. 2. The driving game. A. Overhead representation of the course (circuit). B. Momentary driver's-eye view.

finger. The left thumb operated a directional button that was used to control the right or left direction of the car. Drivers were instructed to finish the designated course as fast as possible. They played the game continuously for up to 40 min, restarting the game if the game ended. We chose *Free play* mode with *Easy* game difficulty level. Drivers drove the *BMW/ R3 743* on a 6.52 km *Road America* track (Fig. 2). We accepted the following default settings; autobrake on, anti-lock brakes on, stability control on, traction control on, automatic shifting, and full suggested line. There were seven other cars on the road. The camera/viewpoint was set at the driver's seat; a first-person perspective. Participants in the Passenger group were instructed to sit comfortably and watch the recording.

At the end of 40 min (or at the time of discontinuation, whichever came first) participants were asked to state, yes or no, whether they were motion sick, after which they filled out the post-exposure SSQ. 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 recoding, the recording was restarted and replayed automatically until 40 min were completed or until the Passenger discontinued, whichever came first.

We assessed motion sickness incidence by asking participants to make a direct, yes/no statements about whether they were motion sick (e.g., Bonnet, Faugloire, Riley, Bardy, & Stoffregen, 2006; Dong et al., 2011; Faugloire, Bonnet, Riley, Bardy, & Stoffregen, 2007; Stoffregen, Faugloire, Yoshida, Flanagan, & Merhi, 2008; Stoffregen & Smart, 1998). Participants were divided into Well and Sick groups based on these explicit verbal statements. When participants stated that they were motion sick, we accepted these statements as veridical.

We assessed the severity of symptoms using the *SSQ* (Kennedy et al., 1993). The SSQ includes 16 questions, which were rated on a 4-point scale. The questions were translated into Chinese.

2.4. Data analysis

We included all participants in our analyses of motion sickness incidence, discontinuation, and symptom severity. We used χ^2 statistics to analyze the data on motion sickness incidence. For symptom severity, we used the Total Severity Score, which was computed in the recommended manner (Kennedy et al., 1993). For inferential tests, we evaluated SSQ data using the Mann-Whitney test and the Wilcoxon signed ranks test. For participants in the Driver group, we used the Mann-Whitney test to analyze data on driving performance.

We separately evaluated the spatial magnitude and the multifractality of movement. We used the standard deviation of position to represent movement magnitude. We evaluated the multifractality of postural activity using multifractal detrended fluctuation analysis, MF-DFA (Ihlen & Vereijken, 2013; Munafo, Diedrick, & Stoffregen, 2017). The range of the singularity exponent, *h(q)*, indicates the heterogeneous nature of multifractal fluctuations (Ihlen, 2012). The width of this range can be used as an index of the degree (or amount) of multifractality in a time series. The range of *h (q)* values is known as the singularity spectrum, or simple the spectrum. The wider the multifractal spectrum, the more multifractal is the movement (Kelty-Stephen, Palatinus, Saltzman, & Dixon, 2013).

We conducted separate analyses of variance (ANOVA) for movement of the head and torso in the AP and ML axes, using between-participants 2 (Control: Drivers vs. Passengers) × 2 (Sickness Groups: Well vs. Sick) designs. We operationalized movement magnitude in terms of positional variability. For movement multifractality, the dependent variable was *W*, the width of the multifractal spectrum. In conducting ANOVA on positional variability and the width of the multifractral spectrum, we estimated the effect size using the η_p^2 statistic. According to Cohen (1988), values of $\eta_p^2 > 0.14$ indicate a large effect, and values of $\eta_p^2 > 0.06$ indicate a medium effect.

We also evaluated coupling of movement between members of each pair of participants. Classically, cross-correlation techniques might be used to quantify coupling of two series of data. However, cross-correlation techniques are sensitive only to linear relations between time series. Postural data commonly are characterized by significant nonlinearities (e.g., Duarte & Zatsiorsky, 2000). For this reason, to quantify interpersonal coupling, we used Average Mutual Information (AMI), a nonlinear 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 evaluates 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.

To analyze the AMI data for Driver-Passenger dyads we used independent sample *t*-tests. In these *t*-tests, when the equal variance assumption was violated, we used the Welch-Satterthwaite method. The Welch-Satterthwaite method yields fractional degrees of freedom, which we report where appropriate. For *t*-tests, we estimated the effect size using the Cohen's *d* statistic. According to Cohen (1988), values of $d > 0.8$ indicate a large effect.

3. Results

3.1. Motion sickness incidence, discontinuation, and driving performance

We classified participants into Well and Sick groups based solely on their responses to the forced-choice, yes/no question, *Are you motion sick?* The incidence of motion sickness for Drivers was 42.31% (11/26), including 6 males and 5 females. Among Passengers, 73.08% (19/26) stated that they were motion sick, including 12 males and 7 females. Using a 2 × 2 contingency table, the difference between Drivers and Passengers was significant, χ^2 (1) = 5.04, p = .025. Motion sickness incidence did not differ between males (69.23%) and females (46.15%), χ^2 (1) = 2.84, p = .092. We further analyzed sex difference in Drivers and Passengers separately. Motion sickness incidence did not differ between male Drivers and female Drivers, χ^2 (1) = 0.16, p = .691; however, the rate did differ between male Passengers (92.31%, 12/13) and female Passengers (53.85%, 7/13), χ^2 (1) = 4.89, p = .027.

Twenty-six participants discontinued without completing the 40-min session. Of these, 9 were Drivers (4 male, 5 female) and 15 were Passengers (9 male, 6 female). At discontinuation, 19 stated that they were motion sick, and were assigned to the Sick group. The remaining 5 (3 Drivers, 2 Passengers) stated that they were not motion sick, and were assigned to the Well group. This latter group gave as reasons for discontinuation heat ("It is too hot"), boredom, tiredness, eye strain, and a sore back. For the sick Drivers, the mean exposure time was 33.05 ± 9.83 min, while for the sick Passengers it was 27.68 ± 11.61 min. Mean exposure time for the well Drivers was 37.59 ± 6.12 min; for the well Passengers it was 36.67 ± 7.26 min.

For participants in the Driver group, driving speed (laps/min) was used to represent driving performance. One driver did not finish the first lap and was excluded from the analysis. Among the remaining participants, driving speed did not differ between the well and sick drivers, $U = 49.00$, $p = .160$.

3.2. Symptom severity

Data on symptom severity are summarized in Fig. 3. At pre-exposure, SSQ scores did not differ between the Well and Sick groups for Drivers, $U = 68.50$, $p = .474$, or for Passengers, $U = 54.50$, $p = .497$. At post-exposure, SSQ scores differed between the Well and Sick groups for Drivers, $U = 5.50$, $p < .001$, and for Passengers, $U = 14.50$, $p = .001$.

Post-exposure scores were higher than pre-exposure scores for the sick Drivers, $Z = -2.94$, $p = .003$, but also for the well Drivers, $Z = -2.21$, $p = .027$. Post-exposure scores were higher than pre-exposure scores for the sick Passengers, $Z = -3.73$, $p < .001$. For the well Passengers, SSQ scores did not differ between pre-exposure and post-exposure, $Z = -1.84$, $p = .066$.

Post-exposure SSQ scores did not differ between sick Drivers and sick Passengers, $U = 69.00$, $p = .134$, or between well Drivers and well Passengers, $U = 49.50$, $p = .837$. These results indicate that control of a virtual vehicle did not influence the severity of post-exposure symptoms.

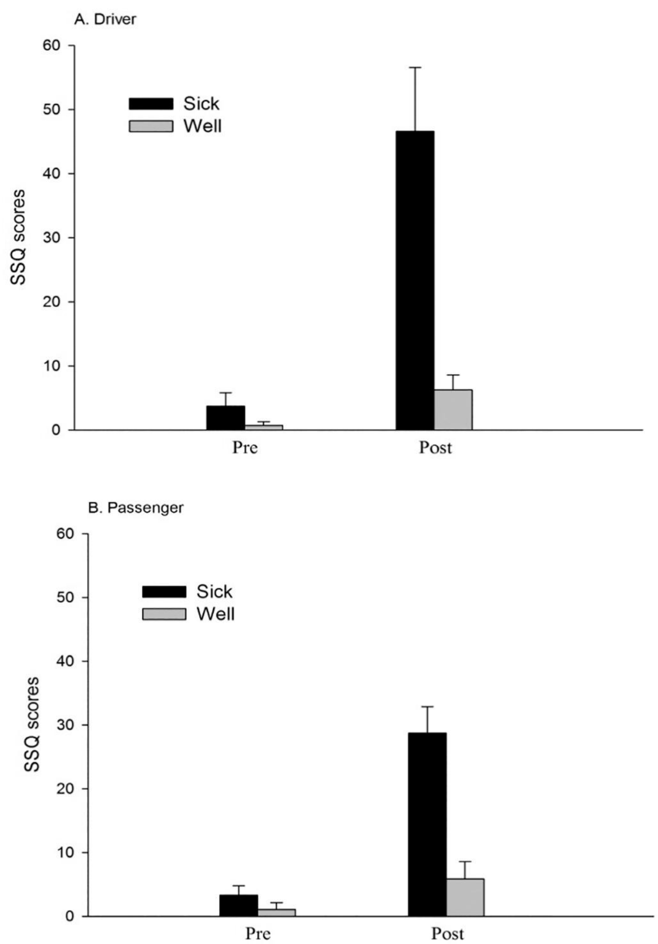

Fig. 3. Symptom severity (SSQ Total Severity Scores) for the Well and Sick groups. Pre: Pre-exposure. Post: Post-exposure. A. Drivers. B. Passengers. The error bars represent the standard error of the mean.

3.3. Movement data

Due to mechanical interference, movement data of one dyad was excluded from our analysis. We judged it to be important to ensure that the movement data represented equivalent exposure durations for different groups. For this reason, for all participants we analyzed movement data corresponding to the participant with the shortest exposure time. This participant was a sick Passenger who discontinued after 9.85 min exposure to the video game. Thus, in analyzing movement, for all participants we considered only movement during the first 9.85 min of exposure to the game.

3.3.1. Positional variability

For movement in the AP axis, there were no significant effects. For the ML axis, the main effect of Control was significant for movement of the head, $F(1, 46) = 8.57$, $p = .005$, $\eta_p^2 = 0.16$, and torso, $F(1, 46) = 7.71$, $p = .008$, $\eta_p^2 = 0.14$ (Fig. 4). For head movement in the ML axis, the main effect of Sickness Groups was significant, $F(1, 46) = 4.08$, $p = .049$, $\eta_p^2 = 0.08$. Positional variability was greater for the Sick group (mean = 1.61 cm, $SD = 0.70$ cm) than for the Well group (mean = 1.40 cm, $SD = 0.78$ cm). There were no other significant effects.

3.3.2. Width of the multifractal spectrum

In the AP axis, the main effect of Control was significant for movement of the head, $F(1, 46) = 17.64$, $p < .001$, $\eta_p^2 = 0.28$, and for movement of the torso, $F(1, 46) = 17.20$, $p < .001$, $\eta_p^2 = 0.27$ (Fig. 5). In the ML axis, the main effect of Control was significant for movement of the head, $F(1, 46) = 10.23$, $p = .003$, $\eta_p^2 = 0.18$, and for movement of the torso, $F(1, 46) = 17.49$, $p < .001$, $\eta_p^2 = 0.28$ (Fig. 5). Finally, for movement of the head in the AP axis the Control × Sickness Groups interaction was significant, $F(1, 46) = 5.41$, $p = .024$, $\eta_p^2 = 0.11$ (Fig. 6). There were no other significant effects.

3.3.3. Coupling between Driver and Passengers

We used AMI to quantify the degree of coupling movements within driver-passenger dyads. Computation of coupling between Drivers and Passengers required 1:1 matching of data points for the two participants in each dyad. Consistent with our other movement data analyses, we analyzed movement data corresponding to the participant with the shortest exposure time. We first analyzed dyads in which the Driver was assigned to the Well group. That is, we contrasted dyads in which both driver and passenger were well (Well-Well) with dyads in which the driver was well and the passenger was sick (Well-Sick). Our analysis included three Well-Well dyads and eleven Well-Sick dyads. We examined values of lag up to and including 10 s.

The absolute value of the maximum observed lag was 10 s. We found a significant main effect of passenger sickness on head movement in the AP axis, $t(11.99) = 3.73$, $p = .003$, $d = 1.44$, 95% CI [0.03, 0.11]. Coupling was stronger in Well-Sick dyads (mean maximum AMI = 0.18, $SD = 0.05$) than in Well-Well dyads (mean maximum AMI = 0.11, $SD = 0.01$). There was no significant effect between Well-Sick dyads and Well-Well dyads in the ML axis of head movement, or in torso movement, each $p > .05$.

In a separate analysis, we analyzed dyads in which the Driver was assigned to the Sick group. That is, we contrasted pairs in which both driver and passenger were sick (Sick-Sick) with pairs in which the driver was sick and the passenger was well (Sick-Well). Our analysis included eight Sick-Sick pairs and three Sick-Well pairs. We examined values of lag up to and including 10 s. The results are illustrated in Fig. 7. The absolute value of the maximum observed lag was 9.83 s. For the AP axis, we found significant main effects of passenger sickness on movement of the head, $t(9) = -2.67$, $p = .026$, $d = 1.98$, 95% CI [−0.13, −0.02], and the torso, $t(9) = -2.86$, $p = .019$. $d = 1.92$, 95% CI [−0.17, 0.01]. There was no significant difference between Sick-Sick pairs and Sick-Well pairs in the ML axis of head or torso movement, $p > .05$.

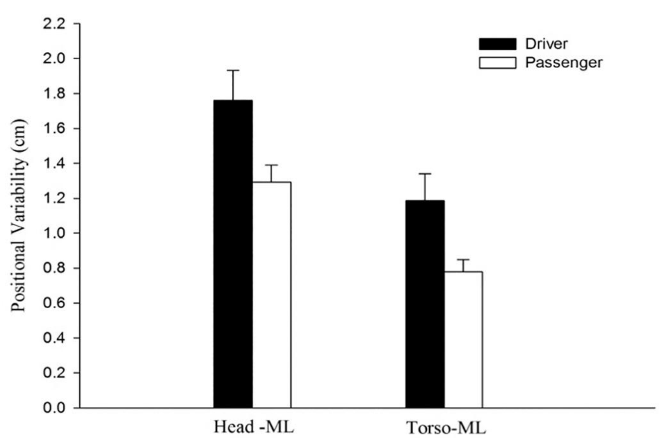

Fig. 4. Positional variability of the head and torso in the ML axis, illustrating statistically significant main effect of Drivers vs. Passengers. The error bars represent the standard error of the mean.

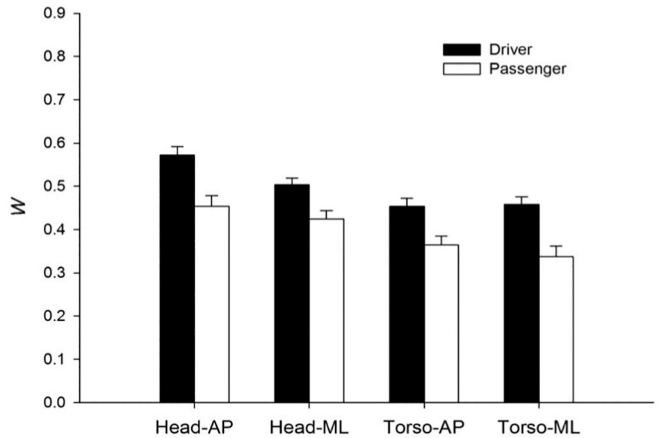

Fig. 5. Width, *W*, of the multifractal spectrum in the AP and ML axes of head and torso movement, illustrating statistically significant main effects of Drivers vs. Passenger. The error bars represent the standard error of the mean.

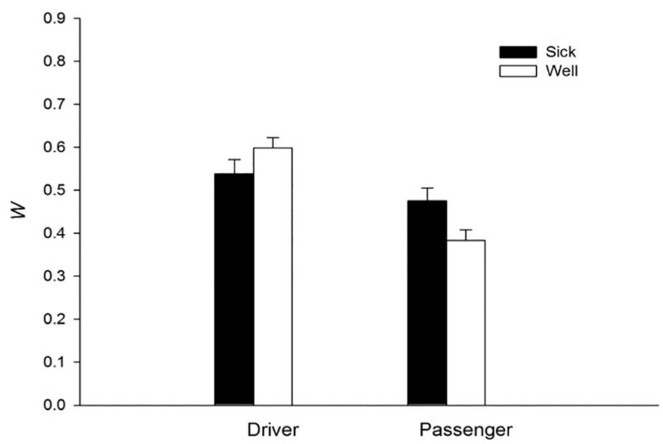

Fig. 6. Width, *W*, of the multifractal spectrum in the AP axis of head movement, illustrating the statistically significant Drivers vs. Passengers × Sickness Groups interaction. The error bars represent the standard error of the mean.

4. Discussion

Pre-adolescent children were exposed to a driving video game. In a yoked-control design, half the children drove the virtual vehicle, while half watched recordings of vehicle motion from their paired Driver, such that members of each pair were exposed to identical visual motion simulation. Consistent with research on adults, Drivers were less likely to report motion sickness than Passengers. During game exposure, movement differed between the Driver and Passenger groups. In addition, movement differed between participants who reported motion sickness and those who did not. We discuss these results in turn.

4.1. The driver-passenger effect in pre-adolescent children

Among pre-adolescent children, we replicated the driver-passenger effect that has been observed among adults (Dong et al., 2011; Rolnick & Lubow, 1991). That is, children in the Passenger group were more likely than children in the Driver group to state that they were motion sick. This result suggests that the driver-passenger effect observed among adults may not be related to adults' experience in driving physical vehicles. Post-exposure symptom severity scores were higher than pre-exposure scores for Drivers who stated that they were not motion sick. This effect is consistent with a common finding among adults, in which exposure to virtual environments yields an increase in symptom severity even among participants who explicitly deny being motion sick (e.g., Stanney et al., 1998).

As expected, after exposure to the virtual vehicle symptom severity ratings were greater among participants who stated that they were sick than among participants who stated that they were not sick. Similarly, for participants who stated that they were motion sick, post-exposure symptom severity ratings were greater than pre-exposure ratings. However, post-exposure symptom severity ratings were greater than pre-exposure ratings among participants who stated that they were not motion sick. That is, there was a disjunction

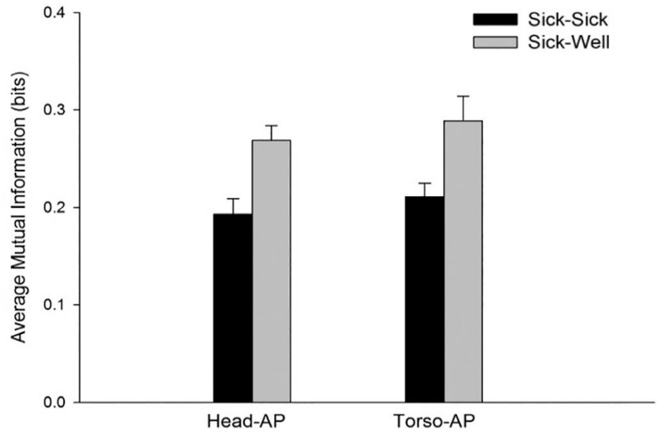

Fig. 7. Average Mutual Information for movement in the AP axis, for Driver-Passenger dyads in which the Driver was assigned to the Sick group. The figure illustrates statistically significant main effects of Passenger sickness. Sick-Sick: Both the Driver and the Passenger were assigned to the Sick group. Sick-Well: The Driver was assigned to the Sick group, and the Passenger was assigned to the Well group. The error bars represent the standard error of the mean.

between symptom ratings and participants' direct statements about their sickness status. This disjunction has been reported in numerous studies with adults (e.g., Chang, Pan, Tseng, & Stoffregen, 2012; Curry et al., 2020; Merhi et al., 2007; Stanney et al., 1998; Stoffregen et al., 2008).

4.2. Drivers and passengers, boys and girls

Among adults, women tend to be more susceptible than men to motion sickness (e.g., Lawther & Griffin, 1988; Munafo et al., 2017; Stoffregen et al., 2017). In the present study, among pre-adolescent Passengers, motion sickness incidence differed significantly between the sexes. However, contrary to previous research with adults, boys were more likely than girls to state that they were motion sick. This finding appears to be novel. Among Drivers, motion sickness incidence did not differ between girls and boys. These results suggest that sex differences in susceptibility to motion sickness may be more labile before puberty than afterward.

4.3. Movement during game exposure

In statistically significant main effects, movement differed between Drivers and Passengers. For positional variability, movement of Drivers and Passengers differed in the ML axis for both the head and torso. As can be seen in Fig. 4, Drivers moved more than Passengers. It is important to note that motion sickness incidence was greater among Passengers despite the fact that the spatial magnitude of movement was greater among Drivers. This finding, which replicates a similar effect observed among adults (Dong et al., 2011), undermines the common assumption that greater movement is equivalent to reduced stability (e.g., Dennison & D'Zmura, 2017). In novel effects, we also found that the multifractality of movement differed between Drivers and Passengers in both the AP and ML axes for both the head and torso (Fig. 5). The fact that movement differed between Drivers and Passengers, independent of motion sickness status, is not surprising. On the one hand, drivers necessarily engage in movement associated with controlling the virtual vehicle, while for passengers such movement was optional. Separately, because drivers were in control, they had the option to engage in postural adjustments to motion of the virtual vehicle that were anticipatory. Because they were not in control of the virtual vehicle, passengers' postural adjustments to vehicle motion necessarily were compensatory (Stoffregen et al., 2017).

Movement differed between children in the Well and Sick groups. Our analysis of the positional variability of movement revealed that participants in the Sick group moved more than participants in the Well group, replicating several previous studies in both adults (e.g., Stoffregen & Smart, 1998) and pre-adolescent children (Chang et al., 2012). Our analysis of movement multifractality revealed a statistically significant interaction of Sickness Groups with control of the virtual vehicle. As can be seen in Fig. 6, relations between Well and Sick participants differed qualitatively between Drivers and Passengers. This qualitative difference is novel (cf. Dong et al., 2011).

Finally, our analysis of movement within driver-passenger dyads revealed that movement coupling of drivers and passengers differed between dyads in which the passenger was sick and dyads in which the passenger was well. This effect was found for dyads in which the Driver was well, replicating effects reported in an earlier study of driving video games (Dong et al., 2011), as well as an earlier study of ambulatory video games (Chen et al., 2012). In a novel analysis, we examined driver-passenger coupling for dyads in which the Driver was sick. This result yielded the novel finding that driver-passenger coupling differed as a function of whether the passenger was well or sick, even when the driver was sick (Fig. 7). It is important to remember that only one participant was in the laboratory at any given time. Coupling between drivers and passengers was not based on any knowledge or awareness of each other. Rather, coupling could arise solely from the visual stimulus of the video game: Visual motion on the screen was identical for the two members of each dyad. Therefore, the measured coupling between drivers and passengers actually reflects the degree to which each of these individuals coupled their own motion to what they were seeing on the screen.

5. Conclusion

In physical automobiles, vehicle motion is the same for all occupants. Despite this identity in stimulus motion, among adults, drivers are less likely than passengers to experience motion sickness (e.g., Rolnick & Lubow, 1991). This driver-passenger effect occurs also among adults in the context of driving video games (Dong et al., 2011), and even among adults in the context of virtual ambulation (Chen et al., 2012). In the present study, we asked whether a similar effect would occur among pre-adolescent children in the context of a driving video game. In a yoked-control design, one member of each dyad of children drove a virtual automobile, after which the second member of the dyad viewed the recorded driving performance. Participants who viewed pre-recorded performances (Passengers) were more likely to state that they were motion sick than participants who controlled the virtual vehicle (Drivers). That is, we confirmed the existence of the driver-passenger effect among pre-adolescent children and, therefore, among a population in which no members had ever driven a physical automobile (cf.Chang et al., 2017 ; Stoffregen et al., 2017).

As noted in Section 1.2, previous studies have shown that adults' postural and subjective responses to virtual vehicles differ substantially depending upon the participants' prior experience driving physical automobiles (Chang et al., 2017; Stoffregen et al., 2017). Because pre-adolescent children have no experience driving physical vehicles, effects of prior driving experience that have been observed in adults cannot exist in pre-adolescent children. Accordingly, the results of the present study demonstrate that the "driver-passenger effect" is not dependent upon prior experience with the control of physical vehicles; that is, the driver-passenger effect occurs among individuals who have never been drivers.

Consistent with research on adults, we found that movement of the head and torso differed between child Drivers and Passengers. In addition, movement differed between participants who, following exposure, stated that they were motion sick, and those who stated that they were not motion sick. Differences were found in the spatial magnitude of movement, but also in an orthogonal measure of the multifractality of movement. Finally, we found evidence of differences between Well and Sick participants in the extent to which postural activity was temporally coupled with motion of the virtual vehicle (cf. Walter et al., 2019). Participants were explicitly and repeatedly instructed to discontinue participation immediately if they experienced any symptoms of motion sickness, however mild. Accordingly, all movement data were collected before the onset of any subjective symptoms of motion sickness. These results are consistent with a prediction of the postural instability theory of motion sickness (Riccio & Stoffregen, 1991).

Declarations of interest

None.

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