Medical & Biological Engineering & Computing (2020) 58:143–154
https://doi.org/10.1007/s11517-019-02070-2

ORIGINAL ARTICLE

# Effects of virtual reality technology locomotive multi-sensory motion stimuli on a user simulator sickness and controller intuitiveness during a navigation task

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Received: 16 November 2018 / Accepted: 5 November 2019 / Published online: 22 November 2019


**Abstract**

Simulator sickness of users and intuitiveness of controllers contribute to a user's acceptance or rejection of a virtual reality (VR) experiment. However, few studies investigated the effects of different VR locomotive controllers and potential gender effects. Hence, we investigated the effects of different motion stimuli combinations and a user's range of neck motion via two experiments in a gender balanced group. Thus, through separate sessions, young adult participants utilized four common VR locomotive controllers (TiltChair, omni-directional treadmill, VRNChair and joystick) with a head-mounted display to execute the same VR navigation task as we measured simulator sickness by the simulator sickness questionnaire and postural sway. Also, we measured intuitiveness through total traversed distance and execution times. As expected, simulator sickness severity increased with VR exposure time. However, participants had significantly shorter traversed distances and execution times when they utilized the TiltChair and joystick respectively; while, participants had significantly longer execution times when they utilized the omni-directional treadmill. Additionally, female participants easily utilized the TiltChair and omni-directional treadmill because they traversed shorter distances than male participants. Therefore, a VR locomotive controller selection should be based on a target population's characteristics to reduce user simulator sickness and to increase controller intuitiveness.

**Keywords** Simulator sickness · Virtual reality · Head-mounted display · Locomotive controller · Multi-sensory integration

## 1 Introduction

Potential simulator sickness develops often from conflicting motion stimuli during a virtual reality (VR) experience; hence, users may find the VR technologies unintuitive because the users struggle to minimize simulator sickness and struggle to interact with the virtual environment. The cause of simulator sickness, as well as other motion sickness types, has been hypothesized by eye movement [10], postural instability [23] and sensory mismatch [21] theories. The eye movement theory describes motion sickness due to one's eyes tracking movement [10]; however, one can still develop motion sickness from closing his/her eyes during motion. In contrast, the postural instability theory describes motion sickness due to one's inability to maintain his/her balance [23]; however, one who is laying down can still develop motion sickness from vertigo. The sensory mismatch theory is generally more accepted because of the above counter arguments against the eye movement and postural instability theories. The popular sensory mismatch theory describes the brain's reaction to abnormal motion stimuli by affecting a user's autonomic system that causes a user to develop simulator sickness [21]. For example, when a seated user utilizes a head-mounted display (HMD) to view a virtual environment and utilizes a joystick to navigate within a virtual environment, the user's eyes would receive visual motion stimuli, while the vestibular (balance organ) and proprioceptive sensory neurons would not receive any rotation or acceleration stimuli. Thus, there will be a mismatch among the sensory inputs. These conflicting motion stimuli between the visual, vestibular and proprioceptive sensory neurons cause the user to develop simulator sickness.

Simulator sickness symptoms as well as their severities can vary among users. Users may develop symptoms related to gastrointestinal distress (nausea, stomach awareness, salivation and burping), visual distress (difficulty focusing, blurred

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vision and headache) and vestibular distress (dizziness and vertigo) [12, 13]. Other physiological responses include an increase in the rate of blinking and respiration [9]. These symptoms may be distracting for a participant to optimally perform a VR task. Furthermore, the symptoms may become so severe that a participant may withdraw from the study. Due to the frequency of simulator sickness occurrence in VR experiments, some studies have investigated novel solutions to mediate simulator sickness such as non-medication treatments, or design of new software techniques and hardware devices.

The investigated simulator sickness non-medication treatments to reduce the symptomatic severities include simultaneous transcutaneous electrical nerve stimulation to either the posterior neck and distal to the right knee [6], or bilaterally on top of the sternocleidomastoid muscles [11]. Even though these treatments have shown to significantly reduce simulator sickness [6, 11], the devices are cumbersome to set up and may interfere with presence and immersion within a VR experience.

To optimize user VR experience, other studies have investigated some new VR software techniques and hardware design. Software techniques to remedy simulator sickness focus on mediating visual optical distress such as constant photon-to-eye latencies, dynamic depth of field or virtual environment design. Photon-to-eye latencies describe the time it takes for an HMD to update the view of the virtual environment in correspondence to a user's head movement. One study showed that varying latency compared to a constant latency significantly increases simulator sickness [27]. Varying latencies may derive from complex computations with an execution time longer than the time between the HMD updates. These computations should execute at a shorter time, or be executed by a parallel processor, to reduce simulator sickness. Visual distress can also be mediated by programming a dynamic depth of field that provides the naturalistic focusing and merging of a binocular image on an HMD [4]. Since a HMD alone does not provide a dynamic depth of field, this may explain the significantly higher simulator sickness users develop in a scene with a higher fidelity environment [7]. Due to higher fidelity environments causing higher simulator sickness, the VR environment should be carefully designed to reduce simulator sickness. By reducing simulator sickness developed from an HMD, VR experiences can now integrate environmental navigation with locomotive hardware controller methods that provide vestibular and proprioceptive sensory matching stimuli.

There have been many studies that developed VR locomotive controllers to reduce simulator sickness. Some studies investigated the utilization of controllers that rely on user in a static location such as gamepad controllers, leaning methods, head tilting methods, hand gesturing and walking in place [14, 30]. In contrast, other studies investigated the utilization of controllers that rely on user in a mobile location with more naturalistic gait methods; those controllers include a manual wheelchair joystick called VRNChair [2], an ultrasonic tracking system [25] and VirtuSphere treadmill system [26]. Only the VRNChair and the ultrasonic tracking system showed significantly lower simulator sickness than the standard gamepad or keyboard inputs [2, 26].

The shortcoming of the above-mentioned controller feasibility studies is that they investigated the utilization of controllers either through static or mobile methods separately. They did not investigate different combinations of motion stimuli for the vestibular, visual and proprioceptive systems altogether. Additionally, the above studies could not investigate any gender effect because they had a very imbalanced number of male/female participants. In this study, we recruited equal number of male and female participants to investigate different locomotive methods between seated static methods (TiltChair, with or without a neck brace, and gamepad joystick) and mobile methods (omni-directional treadmill and VRNChair) with an HMD in terms of the degree of resulted simulated sickness and intuitiveness.

In summary, to investigate the effects of different motion stimuli combinations, we designed two new locomotive controllers: the TiltChair and omni-directional treadmill. These controllers are compared to our previously designed VRNChair [2] and standard gamepad joystick. Additionally, we investigated the effects of neck rotation as we implemented the TiltChair with or without a neck brace. We hypothesized that the VRNChair, which is manual wheelchair joystick, with an HMD minimizes simulator sickness by providing sensory matching motion stimuli to users and optimizes intuitiveness by allowing users to freely move about. Moreover, restrictive neck motion with the TiltChair should reduce simulator sickness because there will be synchronized rotation between the user's neck and torso.

## 2 Methods

### 2.1 Locomotive virtual reality technology

This study utilizes four navigational locomotive controllers (Fig. 1) that include the TiltChair, omni-directional treadmill, VRNChair and joystick with a HMD. These controllers provide different combinations of vestibular and proprioceptive motion stimuli, while the HMD provides visual motion stimuli. The controllers and HMD are further explained in their own respective sections as follow.

#### 2.1.1 TiltChair

The TiltChair (Fig. 1a) consists of a swivel chair with a balance board seat that can rotate along the $z$-axis and $y$-axis. To

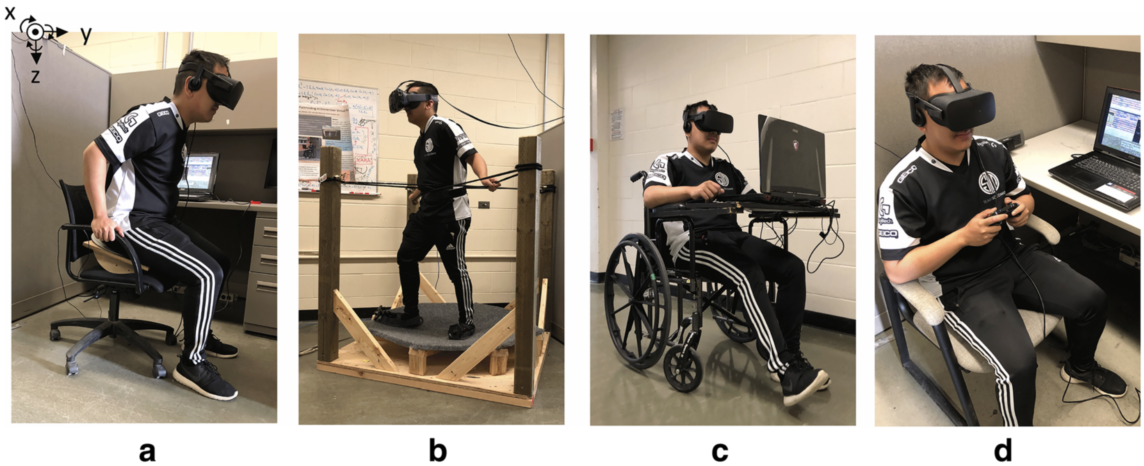


**Fig. 1** Navigation controllers utilized in the experiments. **a** TiltChair with axes of rotation. **b** Omni-directional treadmill. **c** VRNChair. **d** Joystick

determine the rotations along these axes, the balance board seat has an attached microcontroller with a Bosch Sensortec's BNO055 9-axis inertial measurement unit, which has an accelerometer, gyroscope and magnetometer (Fig. 2). This inertial measurement unit calculates an orientational quaternion by integrating accelerometer, gyroscope and magnetometer measurements together. Afterwards, the microcontroller sends the quaternion to the game engine computer via a USB port. From the quaternion, the game engine calculates the change in rotation for input to allow users to interact with the virtual environment. The TiltChair uses the change in rotation along the $z$-axis from a user pivoting in place to change his/her heading direction in the virtual environment; while the TiltChair uses the change in rotation along the $y$-axis from a user's leaning forward to move him/her forward in the virtual environment. The navigation speed within the virtual environment correlates with the angle of a user leaning forward.

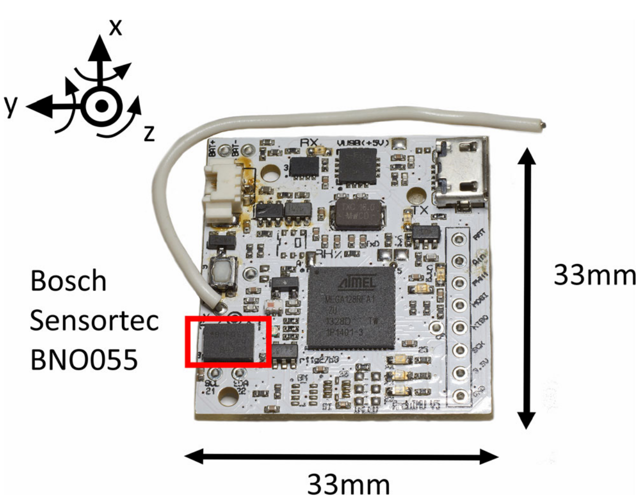


**Fig. 2** Microcontroller with the Bosch Sensortec BNO055 9-axis inertial measurement unit, which has an accelerometer, gyroscope and magnetometer. This provides its orientation as a quaternion via a USB port to a computer game engine. The game engine calculates the change in rotation as input for users to navigate within the virtual environment

Users would experience naturalistic accelerations as they receive vestibular stimuli from leaning forward or pivoting in place. In contrast, users would experience naturalistic speed with zero acceleration as they receive visual stimuli from the HMD in the virtual environment. If users receive only visual stimuli, the feeling of self-perception motion would have latencies [1]. To reduce these latencies, one study utilized the combination of visual and vestibular stimuli [1]. Thus, the participants utilizing the TiltChair would receive vestibular stimuli from leaning forward for pivoting in place, and visual stimuli from the HMD. In Experiment 1, participants utilized the TiltChair without a neck brace, while in Experiment 2 participants utilized the TiltChair with a neck brace (Laerdal Stifneck Select Extrication Collar).

#### 2.1.2 Omni-directional treadmill

The omni-directional treadmill (Fig. 1b) consists of a wooden structure with a central carpeted concave bowl inspired by the Virtuix Omni [28]. Along the walls of the bowl, users with HTC Vive controllers and friction reducing slippers strapped on his/her feet can walk/run. To translate this physical to virtual motion, the Unity game engine obtains a user's feet positions via the HTC Vive hand controllers and utilizes a walking algorithm inspired by a "Walking Velocity Update" [15]. However, instead of utilizing the foot's position relative to a user's body [15], we utilize the foot's position relative to the center of the omni-directional treadmill. Then, the individual's feet positions are utilized to calculate a user's walking velocity to translate the user forward.

Although the omni-directional treadmill is designed to simulate naturalistic gait, it provides conflicting sensory motion stimuli. As a user walks on the omni-directional treadmill, his/her feet alternate between stance and swing phases by muscles contracting and stimulating proprioceptive receptors. Then, a user's head moves forward and backward when he or she transitions from the swing to the stance phases to stimulate the vestibular receptors. Contrarily in naturalistic gait, a walking user's head only moves forward as a user transitions from the stance to swing phases to stimulate the vestibular receptors. Therefore, this sensory conflict of what the brain expects during naturalistic gait may contribute to a user's simulator sickness.

#### 2.1.3 VRNChair

The VRNChair (Fig. 1c) is a manual wheelchair joystick developed by a past research member for intuitive utilization and simulator sickness reduction [2]. Each of the VRNChair's wheels has an individual multi-pole magnetic ring. As the wheels turn with the magnetic rings, a magnetic encoder detects the magnetic changes to generate electrical pulses. These electrical pulses are sent to a microcontroller. Then, the microcontroller estimates the velocity of the wheelchair. Additionally, the same Bosch Sensortec's BNO055 inertial measurement unit as in the TiltChair estimates the VRNChair's heading direction. The microcontroller and inertial measurement unit send the velocity and heading direction respectively to the Unity game engine to move the user in the virtual environment. Overall, the VRNChair stimulates vestibular and proprioceptive receptors as users freely move around.

#### 2.1.4 Joystick

Seated users utilize the joystick from an Xbox Controller (Fig. 1d) to move within the virtual environment. The joystick does not provide any proprioceptive or vestibular motion stimulation.

#### 2.1.5 Head-mounted displays

We utilized two types of HMDs for the omni-directional treadmill's and the other locomotive controllers' individual requirements. The omni-directional treadmill utilizes the HTC hand controllers strapped onto the users' feet, which were only available at the time of the study, to translate the user forward. Contrarily, all other locomotive controllers utilize the Oculus Rift CV1 with the internal orientation tracking ability via its gyroscope, accelerometer and magnetometer sensor fusion. Both HMDs stimulate the visual system with the same resolution 2160 × 1200, and a frame rate of at least 90 Hz. Hence, their differences should not significantly contribute to a user's overall simulator sickness. Furthermore, users can calibrate the HMD interpupillary distance to provide an offset image to each individual eye.

### 2.2 Virtual reality task

Participants completed the same VR task for all sessions. This VR task has been previously designed for our spatial navigation studies to find predefined targets [3, 20]. However, in this study, our primary measure did not include spatial navigation and our participants were all young and healthy so that they could perform well for the test. The VR task consists of a cubic 3-storey building with windows that identify individual rooms. All sides of the building are identical with the same number of rooms, except for the front side that contains a door entrance. Inside the building there are a set of elevators for users to move between floors, but no other landmark cues are provided during a trial.

At the beginning of each trial, the house rotates to show the participants a target room marked with an "X" on its window. Once the participant locates the target room, the participant enters the building from the front to find the current target room. The entire VR task has 8 trials with different targets. Throughout the VR task, we record any potential effects from the different locomotive controllers and HMD via simulator sickness and intuitiveness measurements.

### 2.3 Experiment 1

In Experiment 1, we investigated the effect of different locomotive controllers on a user's simulator sickness and a controller's intuitiveness. The experiment had all participants completing 4 separate sessions for each locomotive controller in a random order: TiltChair without a neck brace, omni-directional treadmill, VRNChair and joystick. We schedule participant sessions to be separated by at least a day to remove any effects of simulator sickness from a prior session.

For experiment 1, twenty participants (10 males) were recruited. The males had an average age of 22.9 ± 2.56 years and females had an average age of 22.8 ± 3.74 years. All participants were physically capable of utilizing the different controllers and did not have any history of vertigo or motion sickness. All participants signed an informed consent approved by the University of Manitoba Biomedical Research Ethics Board prior to being enrolled into the study and in accordance with the latest Declaration of Helsinki.

### 2.4 Experiment 2

In Experiment 2, we investigated the effects of a user's ability to move his/her neck by synchronous neck and torso rotations. To synchronize neck and torso rotations, participants wear a neck brace with an adjustable collar (Laerdal Stifneck Select Extrication Collar). Any new participants are required to complete three separate sessions for the VRNChair, the TiltChair with a neck brace and the TiltChair without a neck brace separated by at least one day to minimize any simulator sickness cross over effects.

We asked all the participants from Experiment 1 for participation. However, two male participants were unavailable at the time of Experiment 2; therefore, two new young adult males were recruited without any issues with physical capabilities and simulator sickness. Participants completed 3 separate sessions to utilize the VRNChair, TiltChair v1 and TiltChair v2. All other participants completed one extra session utilizing the TiltChair with a neck brace and we utilized the data from Experiment 1 for comparisons with the VRNChair and TiltChair without a neck brace. Overall, there were twenty participants (10 males). The males had an average age of 22 ± 2.45 years and females had an average age of 22.8 ± 3.74 years.

### 2.5 Simulator sickness measurements

We measured simulator sickness at baseline before the exposure to the VR task and then after the 1$^{st}$, 4$^{th}$ and 8$^{th}$ (last) trials via two different measurements. We first recorded postural sway measurements (representative of the balance) with eyes open and then eyes closed to calculate the center of pressure path length. Afterwards, we asked participants to complete a simulator sickness questionnaire to calculate different severity scores.

For balance measure, the participants stood on a Wii Balance Board and wear an Oculus Rift HMD as we record postural sway measurements. The participants stand with their arms by their sides and feet at a consistent and comfortable distance apart. The eyes-open condition had participants viewing the VR task building and focusing on an "X" in their center of the view. In contrast, the eyes-closed condition had participants closing their eyes with the HMD displaying a black screen. For both conditions, participants tried to maintain their balance and remain still for one minute. We recorded the Wii Balance Board force sensor values to measure the postural sway.

The Wii Balance Board has been shown to adequately record postural sway with similar results to a gold standard force plate board [5]. We processed the signals obtained from the Wii Balance board by a 4$^{th}$ order low pass filter with a cut-off frequency of 12 Hz [19]. Afterwards, we can calculate *x*- and *y*-coordinates to describe the changes to a participant's center of mass through a center of pressure path length. The center of pressure path length equation is shown below. The TR, BR, TL and BL variables represent the top-right, bottom-right, top-left and bottom-left force sensors respectively; while the COPx and COPy variables represent the x- and *y*-coordinates respectively. For the study, we utilized the change from baseline center of pressure pathlengths after trials 1, 4 and 8.

$$\mathrm{COP_x} = 21 \times \frac{(\mathrm{TR}+\mathrm{BR})-(\mathrm{TL}+\mathrm{BL})}{\mathrm{TR}+\mathrm{TL}+\mathrm{BR}+\mathrm{BL}}$$

$$\mathrm{COP_y} = 12 \times \frac{(\mathrm{TR}+\mathrm{TL})-(\mathrm{BR}+\mathrm{BL})}{\mathrm{TR}+\mathrm{TL}+\mathrm{BR}+\mathrm{BL}}$$

$$\text{Path length} = \sqrt{(\mathrm{COP_{x2}}-\mathrm{COP_{x1}})^2 + \ (\mathrm{COP_{y2}}-\mathrm{COP_{y1}})^2}$$

Afterwards, participants completed a Simulator Sickness Questionnaire (SSQ) [13], which has been utilized in other VR controller and simulator sickness studies [14, 25, 26, 30]. Participants rated the severity of 16 different simulator sickness symptoms based on a 4-point scale. A symptom score with 0 means the least severe, while a symptom score with 4 means the most severe. These symptoms are grouped as Nausea (nausea, stomach awareness, increased salivation, burping), Disorientation (dizziness, vertigo) and Oculomotor (eyestrain, difficulty focusing, blurred vision, headache) to obtain sub-scores. The weighted sum of all the sub-scores can compute the total simulator sickness score. Similar to the center of pressure pathlengths, we utilized the change from baseline scores after trials 1, 4 and 8 for our statistical analysis.

### 2.6 Intuitiveness measurements

The controller intuitiveness measurement consists of the total traversed distance, total execution time and a participant's controller ranking. We calculated the total traversed distance and the total execution time as the sum of traversed distances and execution times from the last four trials respectively. The traverse distance derives from the path a participant navigates from the starting point to the target room. In contrast, the execution time derives from the start of the trial to the instance that the participant enters the target room. We only included the last four trials to remove any learning effects from utilizing the controller for the VR task. Moreover, participants ranked the controllers based on which controller as the most intuitive and most comfortable to utilize and complete the VR task.

### 2.7 Statistical analysis

All data analyses utilize IBM SPSS Statistics version 24 to investigate the effect of different locomotive motion stimuli combinations, which includes neck motion, and the effect of controller intuitiveness. We execute individual three-way mixed analysis of variance (ANOVA) to compare the effect of controller type, gender and VR exposure time on the center of path length mean differences and SSQ mean difference scores. We also executed a two-way mixed ANOVA to compare the effect of controller type and gender on the total traversed distance and total execution time. Any ANOVA with an invalid assumption of sphericity utilizes either the Greenhouse-Geisser or Huynh-Feldt corrections based on the $\varepsilon$ value. If $\varepsilon < 0.75$, the ANOVA utilizes the Greenhouse-Geisser correction; while if $\varepsilon > 0.75$, the ANOVA utilizes the Huynh-Feldt correction [16]. Also, we execute Bonferroni-corrected pairwise comparisons for any ANOVAs with a significant main effect.

## 3 Results

### 3.1 Experiment I

Experiment 1 investigated the effects of different combinations of sensory motion stimuli (visual, vestibular and proprioceptive) provided by locomotive controllers and a HMD on a user's simulator sickness and controller intuitiveness.

#### 3.1.1 Simulator sickness results

For the postural sway measurements, there was only a significant interaction between controller type and sex with users closing their eyes ($F(3, 54) = 3.25$, $p = 0.03$). These results are summarized in Table 1. For the total simulator sickness mean change from baseline scores, VR exposure time had a significant effect ($F(1.21, 21.80) = 21.23$, $p < 0.0005$) as shown in Fig. 3. The largest difference for the SSQ total severity score occurred between baseline and the last trial. Nausea change from baseline score had separate main effects of controller ($F(3, 57) = 4.487$, $p = 0.007$) and VR exposure time ($F(2, 38) = 15.61$, $p < 0.0005$). In contrast, disorientation and oculomotor change from baseline sub-scores had VR exposure time as the only significant main effect: $F(1.25, 23.82) = 12.25$, $p = 0.001$, and $F(1.27, 24.16) = 26.51$, $p < 0.0005$, respectively.

#### 3.1.2 Intuitive measurements

For intuitiveness measures, two-way mixed ANOVA resulted with a significant interaction among sex and controller type on the total traversed distance ($F(32, 54) = 3.24$, $p = 0.029$). Within each sex, controller type had a significant effect on the female's traversed distance ($F(3, 27) = 6.42$, $p = 0.002$), while the males were insignificantly affected by controller type ($F(3, 27) = 2.60$, $p = 0.073$). Within each controller group, there were significant differences between the females and males utilizing the TiltChair without a neck brace ($F(1,18) = 5.00$, $p = 0.038$) and the omni-directional treadmill ($F(1, 18) = 7.26$, $p = 0.015$). The female users utilizing these controller types traversed in shorter distances compared to male users (Fig. 4 and Table 2). Overall, the study's participants traversed at significantly shorter distances while utilizing the TiltChair without a neck brace compared to all other locomotive controllers ($p < 0.03$).

For the total execution time, there was only a significant main effect of controller type ($F(1.28, 23.02) = 61.83$, $p < 0.0005$) as shown in Fig. 5 and Table 3. Participants had significantly shorter total execution times when they utilized the joystick compared to other controller types. In contrast, participants had significantly longer total execution times when they utilized the omni-directional treadmill compared to other controller types. All participants had similar execution times when utilizing the VRNChair and the TiltChair without a neck brace.

The participants ranked the VRNChair and joystick as the most intuitive and comfortable (least causing simulator sickness), while they described the TiltChair without a neck brace and omni-directional treadmill as the least intuitiveness and least comfortable (most causing simulator sickness).

**Table 1** Experiment 1: changes (mean±SD) from baseline center of pressure pathlengths with eyes closed. Values shown are mean differences between baseline and specified trial (cm) with their standard error

| Sex* | Controller Type* | Trial 1 | Trial 4 | Trial 8 |
|---|---|---|---|---|
| Males | VRNChair | − 3.77 ± 18.17 | − 4.82 ± 16.77 | − 5.17 ± 15.69 |
| | Omni-directional treadmill | − 8.53 ± 11.17 | − 1.09 ± 17.14 | 4.79 ± 8.88 |
| | TiltChair (without neck brace) | − 5.69 ± 19.83 | − 0.51 ± 20.21 | − 0.98 ± 20.13 |
| | Joystick | 9.47 ± 20.59 | 14.88 ± 24.57 | 8.64 ± 16.99 |
| Females | VRNChair | − 2.93 ± 12.24 | 2.32 ± 13.08 | − 1.79 ± 16.79 |
| | Omni-directional treadmill | − 0.34 ± 18.56 | 16.60 ± 51.94 | 1.93 ± 23.65 |
| | TiltChair (without neck brace) | − 1.17 ± 7.75 | − 1.21 ± 10.34 | 3.50 ± 16.23 |
| | Joystick | − 6.40 ± 12.05 | − 10.46 ± 13.00 | − 2.01 ± 23.56 |
| Total | VRNChair | − 3.35 ± 15.09 | − 1.25 ± 15.09 | − 3.48 ± 15.91 |
| | Omni-directional treadmill | − 4.43 ± 15.49 | 7.75 ± 38.72 | 3.36 ± 17.45 |
| | TiltChair (without neck brace) | − 3.43 ± 14.83 | − 0.86 ± 15.63 | 1.26 ± 17.95 |
| | Joystick | 1.54 ± 18.32 | 2.21 ± 23.13 | 3.31 ± 20.73 |

*There was only a significant interaction effect ($p < 0.05$) of Sex × Controller Type on the center of path lengths

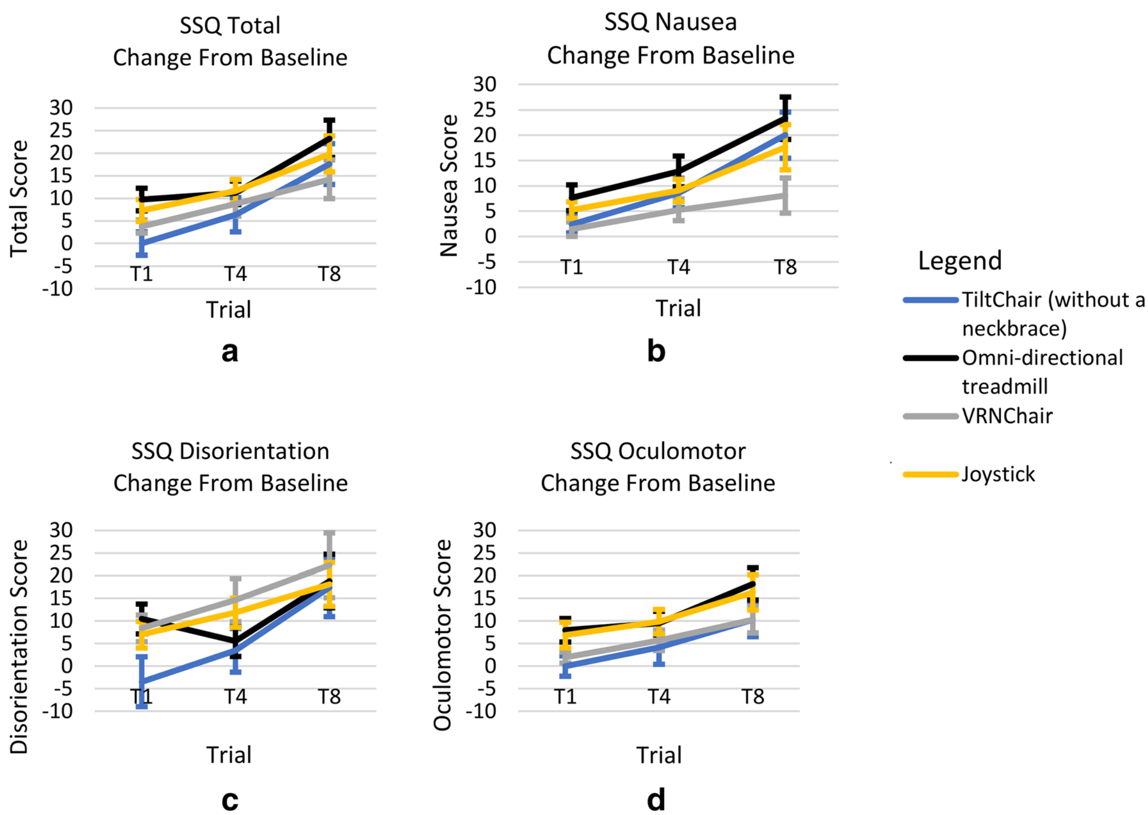


**Fig. 3** Plots of Experiment 1: SSQ change from baseline scores (mean ±SD) for 20 participants. **a** Total change from baseline score. **b** Nausea change from baseline score. **c** Disorientation change from baseline sub-score. **d** Oculomotor change from baseline sub-score. Each line represents the TiltChair (without neck brace) in blue, omni-directional treadmill in black, VRNChair in gray and joystick in yellow. Exposure time had a significant effect on the SSQ total, disorientation and oculomotor scores. In contrast, exposure time and controller type had significant separate main effects on the SSQ naseau score

## 3.2 Experiment 2

Experiment 2 investigated the different effects between restrictive and unrestrictive neck (head) movement provided by a neck brace for the TiltChair. This experiment compared the TiltChair (with or without a neck brace) and the VRNChair on a user's simulator sickness and the controller's intuitiveness.

### 3.2.1 Simulator sickness results

For each controller, Fig. 6 shows the mean SSQ's total, disorientation, nausea and oculomotor change from baseline scores throughout a VR session. The total mean change from baseline scores only had VR exposure time as a significant main effect, $F(1.71, 30.77) = 17.25$, $p < 0.0005$. As the participants had a longer VR exposure time, the higher the total

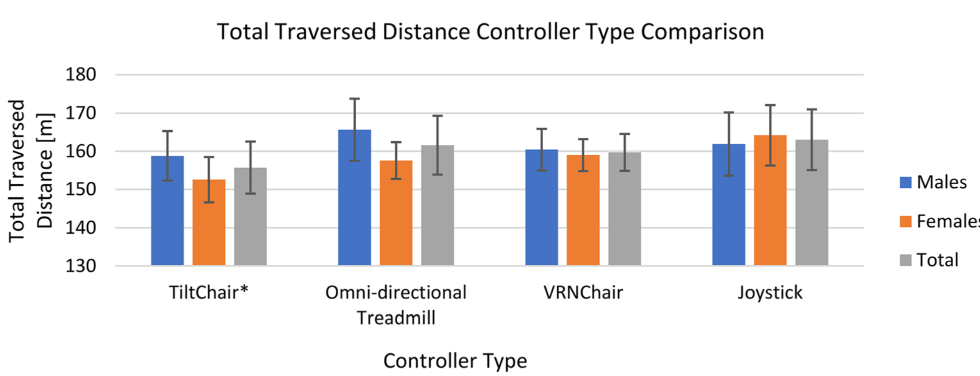


**Fig. 4** Plot of Experiment 1's total traversed distance with standard deviation bars for 20 participants (10 males and 10 females), An asterisk indicates significant effects ($p < 0.05$) between sex, TiltChair (without neck brace) and omni-directional treadmill compared to all other controller types. Female users traversed significantly shorter distances with the TiltChair (without a neckbrace) and omni-directional treadmill compared to male users

**Table 2** Experiment 1: Traversed distance (mean±SD) All units are in meters

| Controller Type | Males | Females | Total |
|---|---|---|---|
| VRNChair | 160.42 ± 5.47 | 159.01 ± 4.21 | 159.72 ± 4.81 |
| Omni-directional treadmill* | 165.64 ± 8.14 | 157.57 ± 4.84 | 161.60 ± 7.72 |
| TiltChair (without neck brace)* | 158.81 ± 6.50 | 152.59 ± 5.92 | 155.70 ± 6.83* |
| Joystick | 161.88 ± 8.27 | 164.18 ± 7.93 | 163.03 ± 7.98 |

*Indicates significance differences with $p < 0.05$. There was a significant interaction between sex and controller type on traversed distances. Within sex, males and females had significant differences while utilizing the omni-directional treadmill and TiltChair (without neck brace). Overall, on average participants traversed significantly shorter distances while utilizing the TiltChair without a neck brace

scores were. However, there were different results for each of the change from baseline sub-scores for disorientation, nausea and oculomotor. The mean disorientation change from baseline sub-score had a significant main effect of controller type ($F(2, 36) = 7.42$, $p = 0.002$) and VR exposure time ($F(1.30, 23.30) = 11.86$, $p < 0.0005$). For Bonferroni-corrected pairwise comparisons on the mean disorientation change from baseline sub-scores, the VRNChair had significantly higher scores compared to the TiltChair with a neck brace (Mean = 13.69, SD = 3.48, $p = 0.003$). In contrast, the nausea and oculomotor mean change from baseline sub-scores only had a main effect of VR exposure time: $F(2, 36) = 13.15$, $p < 0.0005$, and $F(1.61, 29.01) = 17.28$, $p < 0.0005$, respectively.

### 3.2.2 Intuitive measurements results

For intuitive measurements, the interaction among controller type and gender factors had a significant effect on the traverse distance ($F(2,36) = 1.57$, $p = 0.22$). Additionally, the main effect of controller type had a significant effect on the total traversed distance ($F(2,36) = 10.52$, $p < 0.0005$). The controller type main effects can be summarized in Table 4. When analyzing the main effect of controller type with Bonferroni corrections, there were significant differences when comparing the VRNChair to both TiltChairs (as shown in Table 5). Participants traversed longer distances utilizing the VRNChair in comparison to both TiltChair versions. For the total execution time, there was an insignificant effect of controller type and participants had similar total execution times when they utilized the VRNChair and TiltChair with or without a neck brace ($F(2,36) = 2.44$, $p = 0.10$).

## 4 Discussion

In both experiments we investigated the effects of different locomotive VR controllers that compared seated static methods (TiltChair, with or without a neck brace, and gamepad joystick) and mobile methods (omni-directional treadmill and VRNChair) with an HMD on a user's simulator sickness and a controller's level of intuitiveness that has been investigated separately in other studies [2, 14, 25, 26, 30]. The interaction between controller type and VR exposure time had a significant effect on a participant's simulator sickness, while controller type had a significant effect on the controller's level of intuitiveness measures that included the traversed distance and execution time. Previous studies had not investigated the potential gender differences as they did not have a balance number of males/females among their study participants [2, 25, 26, 30]. In this study, we recruited an equal number of male and female participants to further investigate the plausible gender effect on simulator sickness and level of intuitiveness. Our results show gender with controller type had a significant interaction effect on a participant's simulator sickness via postural sway with eyes closed and on a controller's level of intuitiveness measure via traversed distance.

As expected, the controller type with VR exposure time had a significant interaction on the participants' simulator

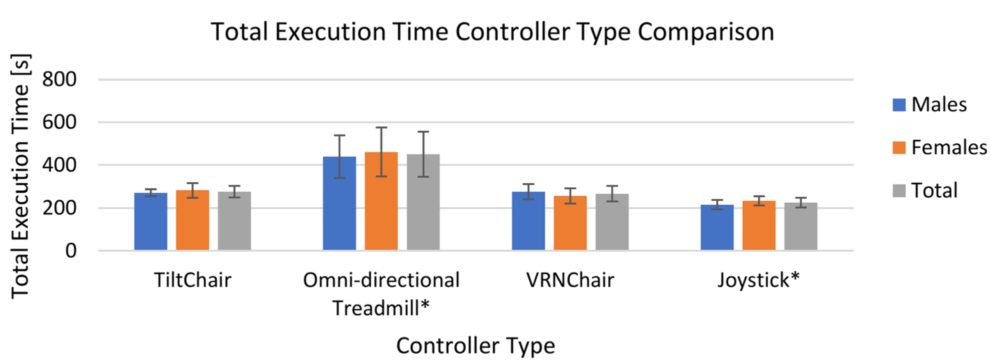


**Fig. 5** Experiment 1: total execution times (mean±SD). An asterisk indicates significant differences ($p < 0.05$) for the omni-directional treadmill and joystick compared to all controller types. The omni-directional treadmill had significantly longer execution times, while the joystick had significantly shorter execution times

**Table 3** Experiment 1: Execution times (mean±SD). All units are in seconds

| Controller Type | Males | Females | Total |
|---|---|---|---|
| VRNChair | 276.14 ± 35.15 | 256.09 ± 34.65 | 266.11 ± 35.49 |
| Omni-directional treadmill* | 439.51 ± 99.71 | 460.77 ± 114.89 | 450.14 ± 105.27 |
| TiltChair (without neck brace) | 271.28 ± 15.65 | 281.68 ± 33.96 | 276.48 ± 26.28 |
| Joystick* | 216.06 ± 21.64 | 234.24 ± 21.30 | 225.15 ± 22.89 |

*Indicates significant differences compared to controller types with $p < 0.05$. The joystick had the significantly shortest execution time and the omni-directional treadmill had the significantly longest execution time. There were insignificant differences between the VRNChair and TiltChair (without neck brace) execution times

sickness due to experiencing different combinations of sensory matching motion stimuli with each controller. For instance, participants utilized two versions of the TiltChair with and without a neck brace; thus, we investigated the effects of synchronized neck and torso rotation. Since the neck brace enforced participants to synchronously rotate their neck and torso, they received vestibular stimuli from the utilization of the TiltChair that matched with the visual stimuli from the HMD. Participants utilizing TiltChair with and without a neck brace did not have significantly different SSQ scores; but after the last trial, the participants had lower SSQ scores with a neck brace compared to without a neck brace. This suggests the importance of sensory matching motion stimuli to minimize simulator sickness symptoms.

Our results indicate the VRNChair provided the most naturalistic and sensory matching motion stimuli evidenced by the lowest SSQ total, nausea and oculomotor scores. We anticipated the VRNChair to have the lowest simulator sickness because participants were sitting in the VRNChair and freely moving in a physical environment in order to move in the virtual environment. Thus, they were receiving a vestibular stimulus synchronous to the visual input they had in VR environment. The mild simulator sickness using the VRNChair might be due to the fact that VRNChair is used in an open area with a ventilation system in place. One participant commented the draft was causing him to feel nauseated. In fact, air flow applied to a user's face can elicit the feeling of motion [24]. The VRNChair would be the most feasible VR controller with minimal simulator sickness compared to other controller types among all participants regardless of sex.

Significant gender effects were observed on postural sway with eyes closed and traversed distance, but not on execution time. Interaction between gender and controller type had a significant effect on the postural sway's change from baseline measurement after VR exposure. Male participants utilizing the joystick had the highest postural sway change from baseline measurement after trial 4; while, female participants utilizing the omni-directional treadmill had the highest postural sway change from baseline measurement after trial 4. Regardless of gender effects, one study observed an insignificant postural sway change from baseline measurement during VR exposure and an insignificant correlation between their mild SSQ scores and postural sway measurements [8]. This study could not investigate any gender effects due to their unequal number of recruited male and female participants [8]. Another study's interaction between gender, self-reported simulator sickness and postural sway methodology had a significant effect on their postural sway measurements before VR exposure [17]. Their female participants that self-reported simulator sickness had lower postural sway than those female participants that self-reported zero simulator sickness; while, their male participants that self-reported simulator sickness had higher postural sway than those male participants that self-reported zero simulator sickness [17]. Hence, the utilization of postural sway to predict or monitor simulator sickness severity may depend on the VR task, VR technology, postural sway methodology and gender effects.

Additionally, gender and controller type had a significant interaction effect on the traversed distance, but not on the execution time. Female participants utilizing the omni-directional treadmill and TiltChair traversed at a shorter distance than male participants. Even though gender did not have a significant effect on execution time, the female participants utilizing these controllers were slower to complete the task than the male participants. Other studies' female participants utilizing a joystick were significantly slower to complete a virtual navigation task with a significantly longer traversed distance than their male participants [18, 22]. This suggests that the current study's female participants easily utilized the omni-directional treadmill because they could slowly turn corners and efficiently navigate towards the target room. Therefore, the female participants traversed shorter distances with longer execution times than the male participants. However, these studies investigated gender differences on spatial performance [18, 22]. We removed any spatial performance differences and learning effects by providing participants verbal guidance towards the target room and by using the data from the last 4 trials. Thus, the gender differences based on traversed distance and execution time were not affected by gender differences based on spatial performance.

Overall, the participants did not have any difficulty using the VRNChair. The male and female participants easily utilized the VRNChair with similar traversed distances and execution times. Without these gender effects, other studies could

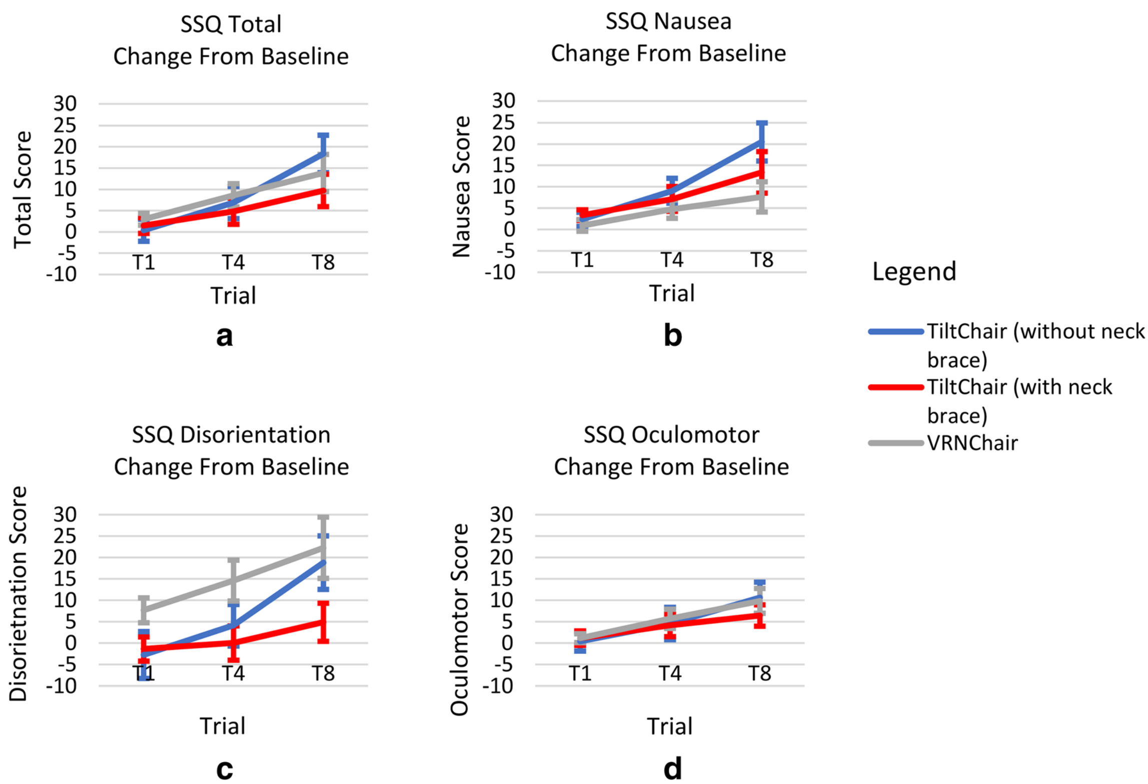


**Fig. 6** Plots of Experiment 2: SSQ change from baseline scores (mean ±SD) for 20 participants. **a** Total change from baseline score. **b** Nausea change from baseline score. **c** Disorientation change from baseline sub-score. **d** Oculomotor change from baseline sub-score. Each line represents the TiltChair (without neck brace) in blue, TiltChair (with neck brace) in red and VRNChair in gray. For the disorientation sub-scores, the VRNChair had significantly higher change from baseline compared to the TiltChair controller

utilize VR and the VRNChair to perform human behavior or performance experiments. In fact, the VRNChair has been utilized in a prior study for the same VR spatial navigation task among healthy young adults, healthy older adults and adults with probable dementia [20]. However, these participants walked and pushed the VRNChair via the handlebars, while they viewed the virtual environment on a laptop screen. In another study, the VRNChair with an Oculus Rift DK2 HMD had healthy young adult participants traversing at shorter distances compared to the laptop screen [29]. Therefore, participants can easily utilize the VRNChair and traverse shorter distances with an HMD.

In contrast, the participants had difficulties utilizing the TiltChair and omni-directional treadmill. Female participants found the TiltChair and omni-directional treadmill easier to utilize than male participants, as described above, with female participants having shorter traversed distances compared to male participants. Regardless of gender, all participants utilizing the omni-directional treadmill had the significantly longest execution times. Participants moved at a slower speed in the virtual environment with an unnaturalistic gait as they walked along the walls of the omni-directional treadmill's concave bowl. Instead of the participants experiencing themselves moving within the virtual environment, they experienced the virtual environment moving passed them. For example, a participant described pushing the virtual environment behind them as they slid his foot from the outer edge to the center of the concave bowl.

Generally, participants with minimal computer experience would struggle to utilize the joystick. When inexperienced navigational video game players utilized a joystick, they had significantly longer execution times and traversed distances than experienced navigational video game players [18]. The authors stated that these inexperienced navigational video game players did not sufficiently practice utilizing the joystick and developing navigational strategies that would help lower their execution times and traversed distances. The current study did not differentiate between inexperienced and experienced video game players. Therefore, we cannot draw any conclusions on the utilization of the joystick among our recruited participants.

**Table 4** Experiment 2: Traversed distances for 20 participants

| Controller Type | Mean ± Standard Deviation [m] |
|---|---|
| VRNChair | 159.87 ± 5.09 |
| TiltChair (without neck brace) | 155.10 ± 6.21 |
| TiltChair (with neck brace) | 154.79 ± 5.06 |

**Table 5** VRNChair comparison to all TiltChair with and without a neck brace for 20 participants

| Controller Type | Mean Difference [m] | Standard Error [m] | *p* value | 95% Confidence Interval [m] |
|---|---|---|---|---|
| TiltChair (without neck brace) | 4.77 | 1.35 | 0.007 | 1.21 to 8.32 |
| TiltChair (with neck brace) | 5.39 | 1.05 | < 0.0005 | 2.63 to 8.16 |

In summary, researchers should carefully select a VR controller to minimize user simulator sickness and maximize a controller's level of intuitiveness. If researchers do not consider these features, participants may compensate their performance to minimize the severity of simulator sickness. Otherwise, participants trying to perform a VR task may be susceptible to simulator sickness that may lead to severe simulator sickness symptoms and withdrawal from the study. Our study recruited healthy young adults with prior computer experience. Therefore, our results should not be applicable for a generalize population. Furthermore, more studies need to investigate the sex effects with different controller types due to prevalent sex bias in relevant studies. Also, researchers could investigate other participant characteristics such as age or cognition.

## 5 Conclusions

Overall the current study provides insights on the comparison among locomotive VR controller methods, which included seated static methods (TiltChair, with or without a neck brace, and gamepad joystick) and mobile methods (omni-directional treadmill and VRNChair) with an HMD; it also considers the effect of gender on the outcomes. The VRNChair was found to be the most feasible controller; it received the lowest SSQ total, nausea and oculomotor scores, and male and female participants had similar traversed distances and execution times. This outcome was expected as the VRNChair provided the most sensory matching and naturalistic motion stimuli. Female participants utilized the TiltChair and omni-directional treadmill more intuitively than the male participants because the female participants efficiently traversed shorter distances than male participants. Thus, researchers who wish to utilize VR need to consider a participant's susceptibility to simulator sickness, gender effects on a controller's level of intuitiveness and other potential participant characteristics that could introduce bias on their experimental measures.

**Acknowledgments** We kindly like to acknowledge Paul J. White for his help in software support and the omni-directional treadmill construction.

**Funding information** The study was supported with funding from the Natural Sciences and Engineering Research Council of Canada (NSERC).

## Compliance with ethical standards

All participants signed an informed consent approved by the University of Manitoba Biomedical Research Ethics Board prior to being enrolled into the study and in accordance with the latest Declaration of Helsinki.

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