Leaning-Based 360° Interfaces: Investigating Virtual Reality Navigation Interfaces with Leaning-Based-Translation and Full-Rotation

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Abstract. Despite recent advances in high quality Head-Mounted Displays (HMDs), designing locomotion interfaces for Virtual Reality (VR) is still challenging, and might contribute to unwanted side effects such as disorientation and motion sickness. To address these issues, we investigated the potentials of leaning-based 360° locomotion interfaces, which provide full-rotational motion cues (unlimited 360° rotations) for rotation, and leaning-based translational motion cues for forward/backward and sideways translation.

In this experiment we compared **joystick** with three locomotion interfaces: **Real-Rotation** (rotation control by an office swivel chair and forward/backward and sideways translations by joystick); **Swivel-Chair** (rotation control by the swivel chair and forward/backward and sideways control by leaning forward/backward and sideways on the chair respectively); **NaviChair** (rotation control by a sit/stand stool and forward/backward and sideway control by weight shifting and leaning in the same direction, which is sensed by a Nintendo's Wii balance board pressure sensors the stool is mounted on).

We asked participants to follow an avatar in an unpredictable curvilinear path in a gamified experiment to evaluate interfaces in terms of different usability aspects, including accuracy, motion sickness, sensation of self-motion, presence, immersion, ease of use, ease of learning, engagement, enjoyment, overall preference, etc. Results did not show any significant advantages of our suggested interfaces over the joystick. But in a sense this is promising because in many aspects, the usability of the proposed interfaces was similar to the well-trained joystick. Moreover, our interfaces had slightly lower motion sickness ratings, and higher sensation of self-motion and spatial presence ratings than the joystick. However, they showed controllability issues, which resulted in significantly lower navigation accuracy (i.e., distance errors) and reduced control precision ratings, which made them less easy to use and comfortable than joystick.

We also discuss the participants' qualitative feedbacks about our interfaces, which shows their strengths and weaknesses, and guide the design of more embodied future VR locomotion interfaces.

Keywords: Virtual reality · Locomotion interface · Leaning-based interface · Motion sickness · Disorientation

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1 Introduction

Recent HMDs (including Oculus Rift and PS4 headset) use game controllers for continuous locomotion in VR games, however when using game controllers or joysticks for locomotion, because the user's body sense no physical motions corresponding to their visual locomotion cues, this conflict between visual, vestibular and proprioceptive sensory data can lead to undesirable side-effects such as spatial disorientation or motion sickness [10, 17]. In order to address these issues and reduce the sensory cues conflict, VR researchers designed many embodied locomotion interfaces, which include at least some physical motions to the user's body.

One of the fairly low-cost solutions for the natural locomotion in VR are the leaning-based locomotion interfaces, where the users lean physically to control their simulated rotational/translational velocity in the Virtual Environment (VE). VR researchers designed many leaning-based locomotion interfaces [1, 6, 16, 22, 24, 26, 31]. Typically, these interfaces use limited leaning-based motion cues to control the simulated translation and limited-rotational motion cues to control the simulated rotation. Many studies investigated the benefits of these leaning-based motion cues on user experience [2, 7, 12–14, 33]. Another fairly low-cost solution for natural locomotion in VR is called Real-Rotation, where the user rotates physically to control the simulated rotation, but uses joystick for forward/backward or sideways translation. This technique, which provides full-rotational but no-translational motion cues was investigated by many researchers such as [4, 8, 25–30, 32].

Each of these two locomotion techniques (i.e., Real-Rotation and leaning-based) have their own strengths. For example, Real-Rotation provides more natural motion cues for rotation, while leaning-based technique provides natural motion cues for translation. Therefore, it might be useful to integrate both techniques as one hybrid technique, where the user physically rotates toward the desired direction and lean to control their simulated translation. This combined technique provides full-rotational/limited-translational motion cues, which has higher fidelity than each of these two techniques to bipedal walking, which is one of the best VR navigation techniques. Therefore, we posit that our suggested technique, provides the richer vestibular/proprioceptive sensory data, which is resulted in less disorientation and motion sickness.

In the current article, we evaluate our new locomotion interfaces, which use full-rotational/leaning-based-translational motion cues, to investigate how integrating full rotational motion cues with limited translational motion cues affects the user experience. To provide a thorough evaluation of our interfaces, not only we measure the introspective data, but also we measured behavioral data including navigation distance/angular errors. The short term benefit of our study is to know if our suggested locomotion interfaces are actually worth to be used in practical applications (such as VR games) rather than joystick. The long term benefit of this study will be to better understand the strengths and weaknesses of using full rotational and limited translational motion cues in VR locomotion interfaces in terms of usability and user experience measures, which can lead us to design better VR locomotion interfaces.

2 Related Works

2.1 Full-Rotational (360° Degrees) Motion

Many researchers investigated if full-rotation of the user's body when rotating in VE help the spatial updating process – the automatic process of updating the spatial awareness of the user while navigating through the environment. However, the results are contradictory, for example, Ruddle and Lessels [28, 29] stated that actual walking is by far better than the Real-Rotation in terms of the user performance in complex tasks (i.e., navigational search task), but Riecke and colleagues [23] performed a similar study with some modifications, and reported that Real-Rotation yielded almost comparable performance to actual walking in terms of search efficiency and time.

One of the practical motivations behind the above studies is the considerable extra cost and effort, which is needed to allow for physical rotations in the VR locomotion interfaces [25], so it is also important to evaluate how physical rotations benefit other important qualities of the user experience (such as immersion, presence, motion sickness, engagement, vection, enjoyment, etc.), which we evaluated in the current study.

2.2 Leaning-Based Locomotion Interfaces

Many studies investigated if limited motion cues benefit the simulated translation within VR in terms of the sensation of self-motion (AKA vection). For example, Groen and Bles [9] showed that the whole body tilt up to 3 degrees/second amplify the vection, and Berger and colleagues [2] reported that the backward tilting on the hexapod motion platform enhance the vection intensity.

As for the leaning-based interfaces, which provide the user-generated limited motions, Riecke and colleagues [22] used a modified wheelchair for VR navigation. The user pushed the wheelchair to forward/backward (up to 8 cm) or rotate it (up to 10°) to control the simulated translation/rotation in the VR, while an elastic band - attached to the wheels - provided a force feedback to return the wheelchair to its center position. The results showed that this limited motion cues increased vection. Specially, Freiberg [7] showed that using NaviChair (a modified version of the stool chair, called Swopper) as a locomotion interface enhances the immersion, presence and enjoyment. Kruijf and colleagues [14] showed that standing leaning enhanced the vection rather than joystick and Riecke et al. [26] showed that leaning forward/backward using as a 'human joystick' metaphor increased enjoyment, engagement, vection and involvement rather than joystick.

One of the important motivations behind all these studies is the simplicity and the low-cost design of the user-generated leaning-based interfaces [12]. Therefore, if our current study shows that combining leaning-based translation with full-rotation will aggregate their benefits, it can be resulted into designing low-cost yet highly usable VR locomotion interfaces eventually.

2.3 Leaning-Based 360° Locomotion Interfaces

Few studies investigated the potentials of the full-rotational leaning-based interfaces. As an example, Marchal et al. (2011) introduced a full-rotational leaning-based locomotion interface for VR – called Joyman - where the user stands on a trampoline, and lean their body to control the simulated velocity/direction by the angle/direction of their body respectively. The preliminary results showed that the Joyman has higher fun, presence and rotation realism, but lower performance (i.e., higher navigational task completion time) than joystick. However, the user should hold the Joyman handles by their hands, which reduces their ability to use their hands for other tasks (such as pointing or interacting with objects) in VR applications [1, 13, 16, 26, 33].

In 2015, Langbehn et al. used leaning to increase the velocity of forward locomotion in Walking-In-Place (WIP) techniques using four Kinect-2 around the user [15]. Not only this interface is expensive, but also like other WIP techniques it has no backward or sideway locomotion. In 2014, Harris and colleagues designed a locomotion interface – called Wii-leaning, where user stand on two Wii Balance Board and put their foot toward the desired direction to control their simulated locomotion [11]. A comparison between Wii-leaning technique with physical-rotation and WIP in pointing task showed that the angular error of Wii-leaning was less than physical-rotation but and 8 (out of 12) participants preferred Wii-leaning than the WIP.

All above full-rotational leaning-based techniques require the user to stand up, which can lead to higher fatigue, discomfort, and leg swelling rather than seated body posture in long periods of time [5]. Specifically as for the leaning-based interfaces, Riecke and colleagues reported that using seated leaning-based locomotion interfaces can be used for longer periods of time rather than standing posture due to user fatigue [26]. Moreover, based on postural instability theory of motion sickness, stronger motion sickness happens in standing body posture comparing to the seated body posture [21]. In 2007, a comparison experiment by Merhi and colleagues also reported that standing VR gamers had significantly higher motion sickness than the seated gamers [19]. As a result, we designed seated hands-free locomotion interfaces with full-rotation and leaning-based translation.

As far as the author knows, very few seated hands-free leaning-based 360° locomotion interfaces have designed. As an example, Nguyen-Vo et al. used a sit/stand stool for VR navigation [20], which we used as one of our interfaces for the comparison purposes. Early VR researchers (such as [6]) discussed our suggested technique as a great interface, but due to the technical issues (such as sensor accuracy and the HMD cable entanglement around the user's neck) did not implement it [12]. New technologies (such as the wireless HTC vive controller) helped us to solve these issues using a simple solution, however, by incoming wireless HMDs (e.g., wireless HTC vive HMD) in a near future, the cable entanglement won't be a problem anymore, which provides a stronger motivation for our research.

2.4 Predictions and Hypotheses

Because of the discussed studies related to the leaning-based-translational motion cues studies, we predicted that our suggested interfaces enhance the vection intensity [14, 26]; immersion, presence [7, 18] and enjoyment [7, 18, 26]. We also predicted that the full-rotational motion cues will help the spatial updating process [23], so it should improve the user performance in velocity/direction control and reduce the distance/angular error. Conversely, we predicted that the joystick can be used for longer periods of time, and also is easier to be learned and easier to be used [7, 14, 18, 26].

3 Study Methodology

The goal of this study was to evaluate four different locomotion interfaces to investigate the potentials of leaning-based 360° locomotion interfaces.

3.1 Participants

We recruited 23 participants (twelve females) SFU students with an average of 21.4 years old. We compensated the participants time by the course credit for the 90 min experiment. Participants had normal or corrected to normal vision and were informed about the potential risks of motion sickness. The local ethics board approved this research. However, because 2 participants excluded due to the technical problems and 7 participants did not finished the experiment due to the motion sickness, we used the data for the other 14 participants.

3.2 Experiment Design and Environment

Controlling velocity and direction is an important task while travelling in many applications (such as games), so we designed the whole experiment to measure how accurate the user can control their velocity and direction.

Although the velocity control is being used in most real-life applications (such as games), but this task is not assumed as an end goal in itself, and when the players are travelling, they have higher important tasks in their minds [3]. However, many VR experimental designs for evaluating locomotion interfaces only focus on the locomotion tasks, which might be resulted into an unnatural situation, and so it might not be easy to generalize their results into the real-life like applications. In order to address this issue, and design an experiment similar to a real-life like application (especially video games), we designed the whole experiment as a sci-fi game, and different phases of our experiment are designed as different levels of the game.

For example, many vection evaluation experiments start with a vection demonstration phase, which familiarizes the user with the vection using a passive locomotion approach. We gamified this phase as the beginning cut-scene of the game, when the player is moving in a volcanic island (Fig. 1) using an airplane, and reads the game story on screen.

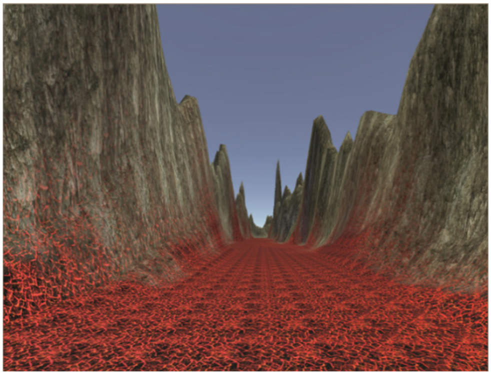

Fig. 1. The experiment environment - A volcanic island

The game narrative happens in a futuristic sci-fi VE, where the robots fight against humans, and one of the human scientists creates a virus to disable the robots brain all together. But when the scientist come to this island - the main base of the robots - to upload the virus, robots capture and imprison him, and now the player's mission is to find, rescue and help him to upload the virus.

After 90 s, the beginning cut-scene will be finished, and the player should play the game using one of the locomotion interfaces. The experiment is a within-subject experiment, so the player plays the game four times, each time with one of the interface. The interfaces assigned to the player by the Latin square order.

3.3 Apparatus and Stimuli

Considering, video games including First Person Shooter (FPS) games can be played usually by joysticks or game controllers with three Degrees of Freedoms (DOFs) - including forward/backward, sideways and rotation, we used these DOFs for all interfaces in our experiments. The maximum forward/backward and sideways velocity was 3 m/s (fast walking speed), and pushing the chairs more than this threshold did not changed the maximum velocity. Also the maximum rotational velocity for the joystick was 30 degrees/second.

As for our interfaces (see Fig. 2), we selected joystick as the standard interface, because it is a standard locomotion interface for VR [18]. Also to understand how adding full-rotational motion cues without any translational motion cues affect the user experience, we added Real-Rotation as our second interface. To investigate how combining forward/backward and sideway translational motion cues with full-rotational motion cues affect the user experience, we added two more interfaces into our experiment conditions.

The first leaning-based 360° interface is called NaviChair –used in [20], where participants sit on a regular sit/stand stool – called Swopper Chair, which is on a Wii Balance Board, so participants can rotate physically to control simulated rotations, and also lean forward/backward and/or sideways to control simulated forward/backward and

Fig. 2. Locomotion interfaces – (top-left) joystick, (top-right) NaviChair, (bottom-left) Real-Rotation, (bottom-right) Swivel-Chair

sideways translations respectively. We added NaviChair to our experiment for comparison purpose and also to have a broader understanding of shared potentials of both our leaning-based 360° interfaces.

The second and last leaning-based 360° interface is called Swivel-Chair, where the user sits on a regular office swivel chair and rotate physically to control simulated rotations, and lean the chair's backrest forward/backward to control simulated forward/backward translations respectively. This means that unlike typical human-joystick approaches (such as [14, 26]), where user lean forward to move forward in VR, in the Swivel-Chair, the user is required to sit straight to move forward with maximum velocity, and if they want to stop moving forward, they need to lean halfway back, and if they want to move backward with maximum velocity, they should lean all the way back.

The reason why we decided to use the straight seated body posture as for forward locomotion, was because leaning forward on a chair for longer periods of time might produce fatigue for the user's back, while leaning straight or backward is more comfortable for the human body. Also, to move sideways with Swivel-Chair, the user need to move their head's position to the right/left. To prevent going sideways by rotating the user's head to left/right, we used the user's neck position, by subtracting the average human head size form the position of the user's forehead position, which is the positional data of HMD. To measure the chair backrest's angle and the user's head distance from the center of the chair, we attached a HTC-vive controller to the chair's backrest.

All the joystick data (either in joystick or Real-Rotation interface) used the velocity control paradigm with linear transfer function, which means that the simulated velocity are related linearly to the deflection of the joystick. All the full-rotations interfaces (including Real-Rotation, Swivel-Chair and NaviChair) used the position control paradigm, where the direction of the user in the virtual world is the same as their direction in the real world. Finally, all the leaning-based translations (in both Swivel-Chair and NaviChair) used the velocity control paradigm with exponential transform function, which means that the simulated translational velocity are related exponentially – by the power of 1.53 – to their deflections.

We chose the exponential transfer function for the leaning-based interfaces based on a pilot study before the experiment, where six participants used our interfaces with both linear and exponential transfer functions and mentioned that they had higher accuracy over the interface control in velocities near zero and slightly less motion sickness.

As for the display, all the interfaces used HTC vive HMD, with 110° of diagonal Field Of View (FOV), 1200 * 1080 pixels resolution (per eye), and 90 Hz update rate. Real-Rotation and Swivel-Chair were designed by attaching a HTC vive controller to the backrest of a regular office swivel chair to measure the backrest's pitch and yaw to control the velocity and direction of the user respectively. We also used a curved rod to hold the HMD cable over the user's head to prevent entangling the cable around while rotation.

3.4 Procedure

After signing the consent form, and the vection demonstration phase, (discussed in Sect. 3.2) participants played the game four times with each of the four interfaces. At the end, we interviewed them to ask for their qualitative feedbacks regarding the interfaces. The game has two levels. In the first level of the game, the player practices how to control the interface. We gamified this task as a mission for the player to search for three prison cells in the environment, and then opening them by pressing the joystick button, to find and rescue the imprisoned scientist (Fig. 3-left).

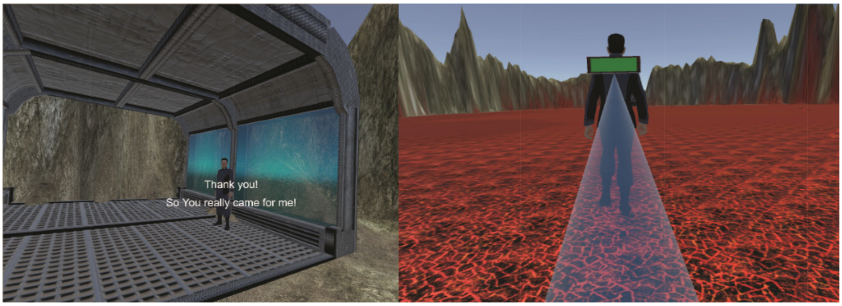

Fig. 3. Experiment levels –(left) level one: Practice the interface by finding the scientist (right) level two: Following the scientist in an unpredictable path

In many games, one of the basic player's tasks is to travel on unpredictable curvilinear paths, we chose this task as for the second level task to test the player's skill with the interface. We gamified this task as where the scientist is training the player on how to follow him within areas filled with lava without being burned. A cooling energy beam coming from the scientist backpack, which protects the player from lava if the player stands on its center, where it hits the ground. The center of this energy field is always four meters behind the scientist, which means that player always need to stay behind him with this distance while following him. To help players see the environment (instead of staring at the ground to find the center of the energy beam), a green bar on the scientist backpack, shows the distance of the player from the center of the protective energy field (Fig. 3-right).

In order to help the player practice this task, the player practice this task two times at the beginning of this level. In the first practice trial, he/she need to follow the scientist in a straight path for 10 s, and in the second practice trial, they need to follow the scientist in a slightly curved path for another 10 s. Then the player need to do the same for three test trials, where each of them takes about 30 s, and the scientist walks with 2 m/s velocity, and change his direction continually with the maximum rotation speed up to 22 degrees/second.

After finishing all three test trials, the level is finished, and the player should answer the post-trial questionnaire (including 15 questions) about the interfaces. We will explain these questions at the result section.

4 Results

In this section, first we report the analysis of our quantitative data and then report the participant comments in the post-experiment interview about the interfaces as a qualitative approach. To analyze our quantitative data, we performed 1-way within-subject two-tailed ANOVA on both our behavioral and introspective measures. As for the behavioral measures, we analyzed the participant's position data to calculate their accuracy in terms of both distance and angular errors, and as for the introspective data, we analyzed their answers to 15 questions about each interface, which were a continuous rate between 0 ~ 100%.

4.1 Behavioral Results

As for the behavioral measures, considering both distance and angular error data were skewed negatively (toward zero), we converted them to logarithmic scales, and Shapiro Wilkes test showed the normality of the scaled data.

Accuracy of Each Interface. Mauchly's test showed the violation of sphericity assumption for both overall distance and angular error, so we performed the Greenhouse-Geisser correction of ANOVA, which showed no significant difference in terms of angular error. However the Greenhouse-Geisser correction of ANOVA showed that the interface has a significant effect on distance error ($F(1.55, 20.2) = 5.53$, $p = .017$, $\eta_p^2 = .298$). Tukey HSD post hoc showed that NaviChair ($M = 2.26$ m, $SD = 1.59$ m) had higher distance error than both Joystick ($M = 1.76$ m, $SD = 2.01$ m) and Real-Rotation ($M = 1.43$ m, $SD = 1.39$ m) (all ps < .010) (Fig. 4).

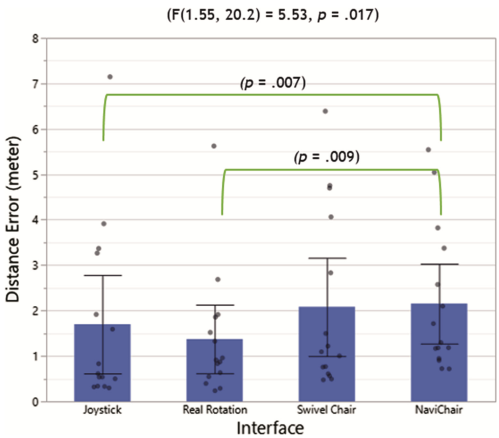

Fig. 4. Average of distance error for each interface. Dots present individual participant's mean data (CI = 95%)

Accuracy of Each Trial (Learning Effect). Beside interfaces, which affect the average distance error of participants, we also compared the overall distance error of participants for each trial. Considering the Mauchly's test showed violation of the sphericity assumption, we performed the Greenhouse-Geisser correction of ANOVA, which showed a significant effect of trials over distance error ($F(1.88, 24.4) = 3.73$, $p = .040$, $\eta_p^2 = .223$). Tukey HSD post hoc showed that the average distance error of first trial ($M = 2.14$ m, $SD = 2.17$ m) had higher distance error than the third trial ($M = 1.66$ m, $SD = 1.61$ m) ($p = .030$), which shows a learning effect. But there were no significant effect for second trial ($M = 1.89$ m, $SD = 1.85$ m) (Fig. 5).

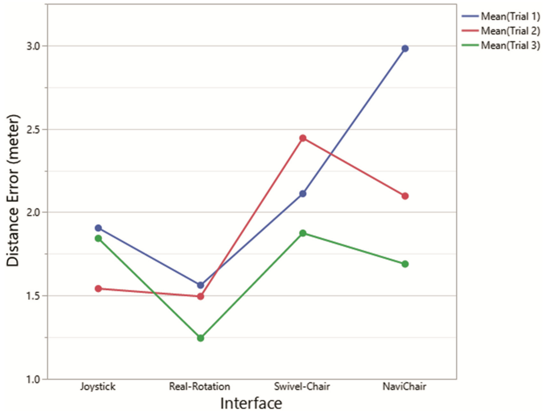

Fig. 5. The average of participant's distance errors for each interface at each trial.

4.2 Introspective Results

Shapiro Wilkes test showed that the introspective data were normal or had small violation of normality, which ANOVA is robust enough for the small normality violations. The Mauchly's test showed the violation of the sphericity assumption for all the measured variables, so we performed the Greenhouse-Geisser correction of ANOVA for all the variables, and all the significant effects have been mentioned at below sections ($p < .05$). All other results were not significant including immersion, enjoyment, learnability, and overall preference.

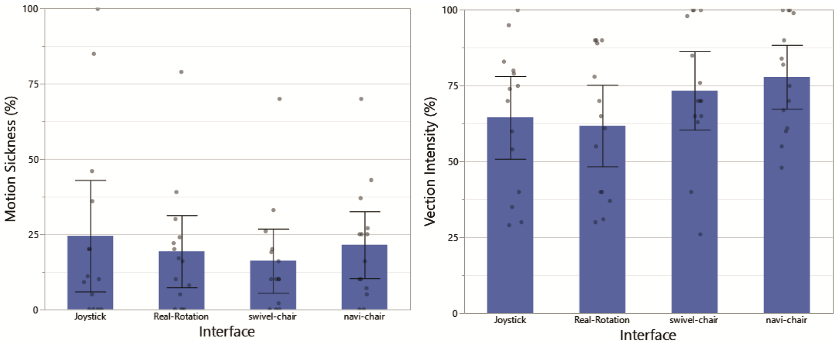

Fig. 6. (Left) Average of motion sickness for each interface (right) average of vection intensity for each interfaceDots present individual participant's data. (CI = 95%)

Motion Sickness. The results showed no significant effect of interfaces on motion sickness ($F(1.34, 17.7) = .170$, $p = .750$). However, swivel-chair had the lowest average of motion sickness (M = 16.1%, SD = 18.5%), which is followed by Real-Rotation (M = 19.3%, SD = 20.8%) and then NaviChair (M = 21.4%, SD = 19.3%), and joystick had the highest average of motion sickness (M = 24.4%, SD = 32.1%) (Fig. 6-left).

Vection Intensity. The results showed no significant effect of interfaces on the vection intensity ($F(2.36, 30.6) = 3.09$, $p = .052$). However, NaviChair had the highest average of vection intensity (M = 77.9%, SD = 18.2%), which if followed by Swivel-Chair (M = 73.4%, SD = 22.4%), and then Joystick (M = 64.6%, SD = 23.6%), and Real-Rotation had the lowest average of vection intensity (M = 61.8%, SD = 23.3%) (Fig. 6-right).

Spatial Presence. The results showed no significant effect of interfaces on the spatial presence (being there physically) ($F(2.12, 29.6) = 2.15$, $p = .132$).However, NaviChair had the highest average of spatial presence (M = 69.1%, SD = 21.7%), which is followed by Swivel-Chair (M = 65.6%, SD = 20.5%), and then Real-Rotation (M = 57.9%, SD = 17.5%), and joystick had the lowest average of presence (M = 54.6%, SD = 21%) (Fig. 7-left).

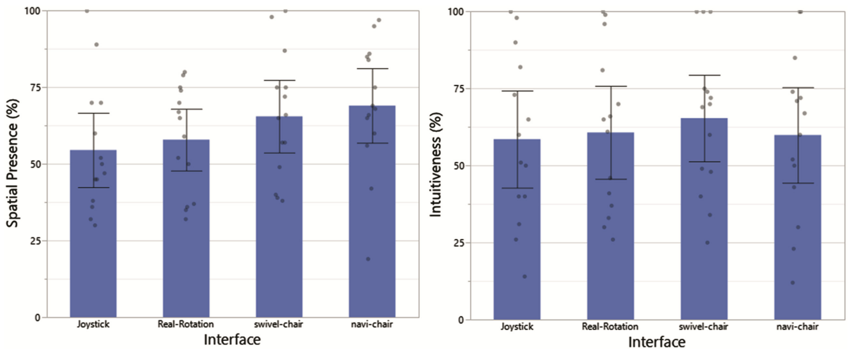

Fig. 7. (Left) Average of spatial presence for each interface (Right) average of intuitiveness for each interfaceDots present individual participant's data. (CI = 95%)

Intuitiveness. The results showed no significant effect of interfaces on the intuitiveness ($F(2.12, 27.6) = .292$, $p = .761$). However, there were slight differences in terms of intuitiveness average. Swivel-Chair had highest average of intuitiveness (M = 65.4%, SD = 24.3%), which is followed by Real-Rotation (M = 60.8%, SD = 26.1%), and then NaviChair (M = 59.9%, SD = 26.8%), and Joystick had the lowest average of intuitiveness (M = 58.6%, SD = 27.3%) (Fig. 7-right).

Precise Control. The results showed that the interface had a significant effect on the precise control ($F(2.55, 33.2) = 9.01$, $p = .0003, \eta_p^2 = .409$). Tukey HSD post-hoc showed that joystick (M = 75, SD = 23.9) had significantly higher precise control than both Swivel-Chair (M = 49.8%, SD = 29.9%) and NaviChair (M = 32.3%, SD = 18.7%) (all $ps < .021$). Moreover, Real-Rotation (M = 54.8%, SD = 20.7) had significant higher precise control than NaviChair ($p = .046$) (Fig. 8-left).

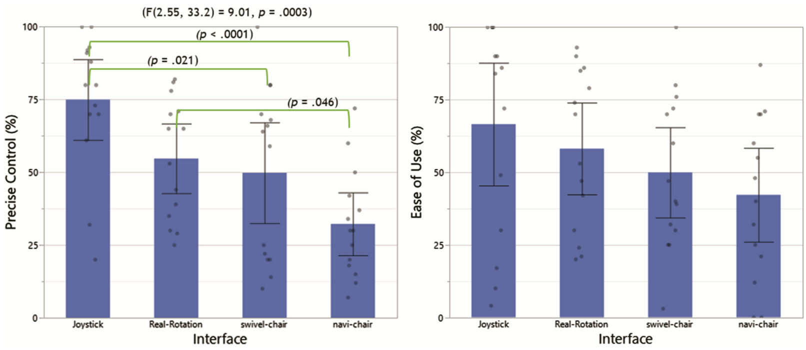

Fig. 8. (Left) Average of precise control for each interface (Right) ease of use average for each interface. Dots present individual participant's data. (CI = 95%)

Ease of Use. The results showed no significant effect of interfaces on the ease of use ($F(2.15, 28.0) = 2.09$, $p = .139$). However, Joystick had the highest ease of use mean ($M = 66.6\%$, $SD = 36.7\%$), which is followed by Real-Rotation ($M = 58.1\%$, $SD = 27.4\%$), and then Swivel-Chair ($M = 49.9\%$, $SD = 27.0\%$), and NaviChair had the lowest ease of use ($M = 42.2\%$, $SD = 28.0\%$) (Fig. 8-right).

Comfort. The results showed that the interface has a significant effect on the comfort ($F(1.37, 17.9) = 4.08$, $p = .048$, $\eta_p^2 = .239$). Tukey HSD post-hoc showed that joystick ($M = 71.4\%$, $SD = 32.3\%$) had higher comfort than NaviChair ($M = 43.3\%$, $SD = 28.9\%$) ($p = .010$). There were no other significant effect on comfort for other interfaces including Real-Rotation ($M = 65.1\%$, $SD = 28.0\%$) and Swivel-Chair ($M = 58.9\%$, $SD = 23.1\%$) (Fig. 9-left).

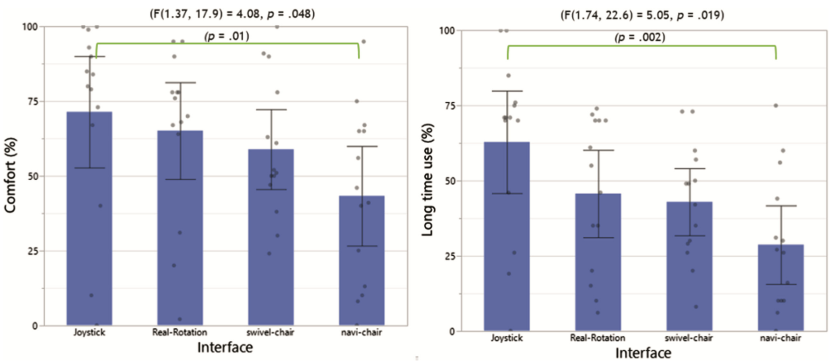

Fig. 9. (Left) Comfort mean for each interface (right) longevity mean for each interface. Dots present individual participant's data(CI = 95%)

Long Time Use (i.e., Longevity). The results showed that the interface had a significant effect on the longevity ($F(1.74, 22.6) = 5.05$, $p = .019$, $\eta_p^2 = .280$). Tukey HSD post-hoc showed that participants could imagine using joystick ($M = 62.8\%$, $SD = 29.6\%$)

for longer periods of time than NaviChair ($M = 28.6\%$, $SD = 22.6\%$) ($p = .002$). There were no other significant effect on longevity for other interfaces including Real-Rotation ($M = 45.6\%$, $SD = 25.2\%$) and Swivel-Chair ($M = 42.9\%$, $SD = 19.4\%$) (Fig. 9-right).

Problems Using the Interface. The results showed that the interface has a significant effect on the reported problems ($F(2.31, 30.1) = 5.00$, $p = .010$, $\eta_p^2 = .278$). Tukey HSD post-hoc showed that participants had significantly less problems using joystick ($M = 21.4\%$, $SD = 19.1\%$) rather than NaviChair ($M = 54.6\%$, $SD = 23.6\%$) ($p = .002$). There were no other significant effect on problems using interfaces for other interfaces including Real-Rotation ($M = 38.6\%$, $SD = 27.7\%$) and Swivel-Chair ($M = 42.3\%$, $SD = 28\%$) (Fig. 10-left).

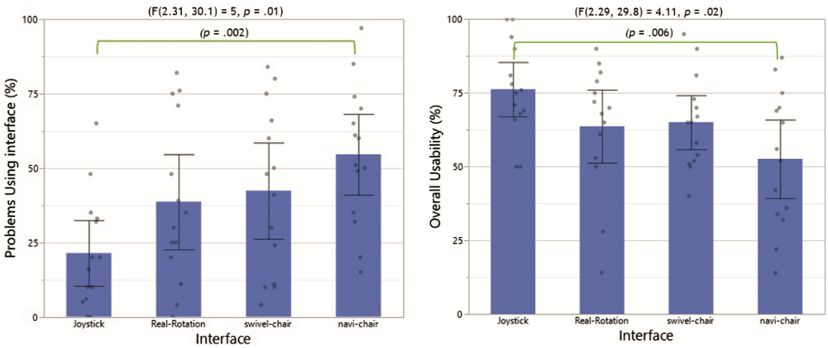

Fig. 10. (Left) Average of user problems with each interface (right) average of overall usability for each interfaceDots present individual participant's data (CI = 95%)

Overall Usability. The results showed that the interface has a significant effect on the overall usability ($F(2.29, 29.8) = 4.11$, $p = .020$, $\eta_p^2 = .240$). Tukey HSD post-hoc showed that joystick ($M = 76.3\%$, $SD = 15.9\%$) had higher overall usability than NaviChair ($M = 52.6\%$, $SD = 23.1\%$) ($p = .006$). There were no other significant effect on overall usability for other interfaces including Real-Rotation ($M = 63.7\%$, $SD = 21.5\%$) and Swivel-Chair ($M = 65.1\%$, $SD = 15.8\%$) (Fig. 10-right).

4.3 Qualitative Results

After finishing the experiment, we interviewed each participant and ask them which interfaces they enjoyed and why? We also asked about the problems they had with any of the interfaces. These qualitative data will be reported in this section, to shed a light on strengths and weaknesses of each interface. This feedbacks also can be useful for future improvement of the interfaces.

Joystick Feedbacks. Two (out of 14) participants enjoyed joystick over the other interfaces, because they were used to it or it was comfortable for them. However, as for the problems of joystick, some participants mentioned that joystick locomotion was not natural, and two of them mentioned that they also rotated their neck instead of rotating joystick. One participant suggested to use game controllers instead of joystick, because he were more familiar with the game controllers.

Real-Rotation Feedbacks. Five (out of 14) participants enjoyed Real-Rotation over the other interfaces, because physical rotation helped them to be immersed in the VR, but also they could precisely control their speed with joystick. However, as for the problems of Real-Rotation, four participants mentioned that it was not easy to control two interfaces (i.e., chair for rotation and joystick for translation) simultaneously, and they were disconnected from the game.

Swivel-Chair Feedbacks. Five (out of 14) participants enjoyed Swivel-Chair over the other interfaces, because it was a comfortable chair and intuitive. Four participants also mentioned that it was highly intuitive and natural, which made them highly engaged into the game. However, as for the problems of Swivel-Chair, five participants mentioned that it was not easy for them to control the speed by leaning back, so they could not control their speed precisely.

NaviChair Feedbacks. Two (out of 14) participants enjoyed NaviChair over the other interfaces, because it was comfortable for them, so engaged and immersed them into the game. However, as for the problems of NaviChair, eight participants mentioned that it was hard for them to control it accurately. One of them mentioned that it was hard to focus on the bottom of their body to navigate, another participant mentioned that due to her back problem. One participant mentioned that it was hard to stop NaviChair, and another one mentioned that it was too sensitive. Two participants mentioned that it was too loose and jumpy. Because NaviChair was over the Wii Balance Board, even its lowest height was too high for some participants, so three participants mentioned that the height of NaviChair was too high for them. One participant mentioned that NaviChair is an interesting interface for free exploration of VE but not for accurate maneuvering purposes.

5 Discussion and Conclusions

The experiment results did not confirmed many of the predicted advantages of leaning-based 360° interfaces over joystick or vice versa significantly. However, the slight difference between measured data means seems promising. For example, as we predicted about the low motion sickness of our interfaces, the motion sickness average of both Swivel-Chair and NaviChair is slightly lower than joystick. Especially, Swivel-Chair has slightly lower motion sickness average than Real-Rotation as well, which shows that adding leaning-based translation to a full-Rotational interface trends to reduce motion sickness.

Beside that, as we predicted based on the previous studies (i.e., [14, 26]), both Swivel-Chair and NaviChair had slightly higher vection intensity average than the joystick and Real-Rotation. Also as for the presence, as we predicted [7, 18], both Swivel-Chair and NaviChair had slightly higher spatial presence average than joystick and Real-Rotation.

As for the joystick advantages, as we predicted [7, 14, 18, 26], joystick showed significantly higher precise control, comfort, longevity, and overall usability than

NaviChair, but comparing to Swivel-Chair, it had only higher precise control. The results of this experiment, also rejected some of our predictions. For example, unlike our prediction about the higher accuracy of NaviChair (i.e., lower navigational distance errors) [23], it had significantly lower accuracy than both joystick and Real-Rotation.

Overall, the results suggest the potentials of leaning-based 360° interfaces, however they still have controllability issues and need to be improved in terms of precise control, ease of use, comfort, longevity, and overall usability. One of the possible explanations for our non-significant results might be because of using only 14 participants with huge between-subject variability, which can be resulted into the limited power of the test.

As for the design guidelines to improve our suggested interfaces, as mentioned in the participant's feedback section, NaviChair can be improved in many aspects (e.g., height, loose and jumpy seat, etc.). As for the Swivel-chair, participants did not mention many problems regarding the sideways controllability by their neck muscles, but instead mentioned that controlling forward/backward motion by their back muscles was not easy. Therefore, it might be useful to control both forward/backward and sideways locomotion using neck muscles, which is more accurate than the back muscles. It means that the simulated forward/backward and sideways locomotion can be controlled by moving the head forward/backward and sideways respectively.

Overall, our results suggest that using leaning-based 360° locomotion interfaces might be promising, however our interfaces need to be improved. Moreover, our experiment was a simple avatar-following task without of spatial orientation or navigational tasks, which are important tasks in many VR applications (especially games), and should be done in future experiments. Beside that, if we compare leaning-based 360° interfaces with joystick or Real-Rotation in an experiment, which needs interaction with the environment, because both our leaning-based 360° interfaces (i.e., Swivel-Chair and NaviChair) provide hands-free locomotion, the users can use their hands for natural interaction with the environment (such as pointing and shooting enemies in a FPS game by gun), which joystick and Real-Rotation have no such natural hand interaction. Such an experiment also can investigate other potentials of our suggested interfaces as a joystick for VR applications.

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