Intentional Head-Motion Assisted Locomotion for Reducing Cybersickness

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Abstract—We present an efficient locomotion technique that can reduce cybersickness through aligning the visual and vestibular induced self-motion illusion. Our locomotion technique stimulates proprioception consistent with the visual sense by intentional head motion, which includes both the head's translational movement and yaw rotation. A locomotion event is triggered by the hand-held controller together with an intended physical head motion simultaneously. Based on our method, we further explore the connections between the level of cybersickness and the velocity of self motion through a series of experiments. We first conduct Experiment 1 to investigate the cybersickness induced by different translation velocities using our method and then conduct Experiment 2 to investigate the cybersickness induced by different angular velocities. Our user studies from these two experiments reveal a new finding on the correlation between translation/angular velocities and the level of cybersickness. The cybersickness is greatest at the lowest velocity using our method, and the statistical analysis also indicates a possible U-shaped relation between the translation/angular velocity and cybersickness degree. Finally, we conduct Experiment 3 to evaluate the performances of our method and other commonly-used locomotion approaches, i.e., joystick-based steering and teleportation. The results show that our method can significantly reduce cybersickness compared with the joystick-based steering and obtain a higher presence compared with the teleportation. These advantages demonstrate that our method can be an optional locomotion solution for immersive VR applications using commercially available HMD suites only.

Index Terms—locomotion, cybersickness, head motion, translation, rotation, velocity, presence

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1 INTRODUCTION

V IRTUAL reality (VR) applications using head-mounted displays (HMDs) have become very popular in recent years with the affordance of high presence in immersive virtual environments (VEs). When a user moves in the physical world, the user will feel that he walks over the same distance in the virtual environment, making himself feel really in the VE. However, the physical space available is generally limited. Therefore, locomotion technique is one of the key solutions to help the users move over a long distance in an immersive virtual environment while keeping themselves staying in a tiny physical area [1].

Steering locomotion is a commonly used locomotion technique [2], of which joystick-based steering (abbr. JS) utilizes joysticks to help the user smoothly move or turn in the VEs. Generally, steering locomotion can bring high presence but may induce strong cybersickness (motion sickness in VEs) [2]. In addition to steering locomotion, walking-based methods [3], [4], [5] and leaning-based methods [6] are used for locomotion. However, walking-based methods may induce increased tiredness and fear of collision (e.g., walking-in-place technique [7]). Leaning-based locomotion techniques were found to have no significant difference on cybersickness with JS [8], [9] or show even higher cybersickness than JS [10]. Cybersickness is one of the most important problems of VR systems, and the existence of cybersickness will significantly influence the comfort of the users [11].

Therefore, to reduce cybersickness when performing locomotion is crucial for virtual reality applications. Redirected walking (RW) may be a solution to locomotion, but it generally requires a relatively large space [12], [13], [14], [15]. Teleportation (TP) [16] is a widely used locomotion technique that can induce less cybersickness than JS. However, TP was found to perform worse in the aspect of presence due to unnatural movement [7]. Given that presence is one of the most critical features of VR applications [17], it is necessary to explore a new locomotion technique that can dramatically reduce cybersickness while maintaining a high level presence.

Our goal is to develop a new locomotion technique that reduces the users' cybersickness and provides a high presence using the commercially available HMD suite only. In principle, a mismatch between efferent (expected) and sensory (actual) movement is probably the primary cause of motion sickness [18] and contributes to cybersickness [19]. Moreover, Harris et al. [20] found that a complete consistency between visual and vestibular cues was not necessary to help induce sickness-free self-motion. Originating from this finding, we design a simple and efficient locomotion technique based on intentional head motion (actively physical movement) to maximize the synchronization of the visual and vestibular induced self-motion illusion, i.e., making the vestibular system's sense always consistent with the visual perception in the coherent direction of acceleration. When our method is activated, the visual self-motion illusion is coherent with the proprioception from intentional head motion in direction but has a different speed for locomotion. Proprioception refers to knowledge of one's own movement, action, and location, especially the collective mechanoreceptors information during self-movement of a
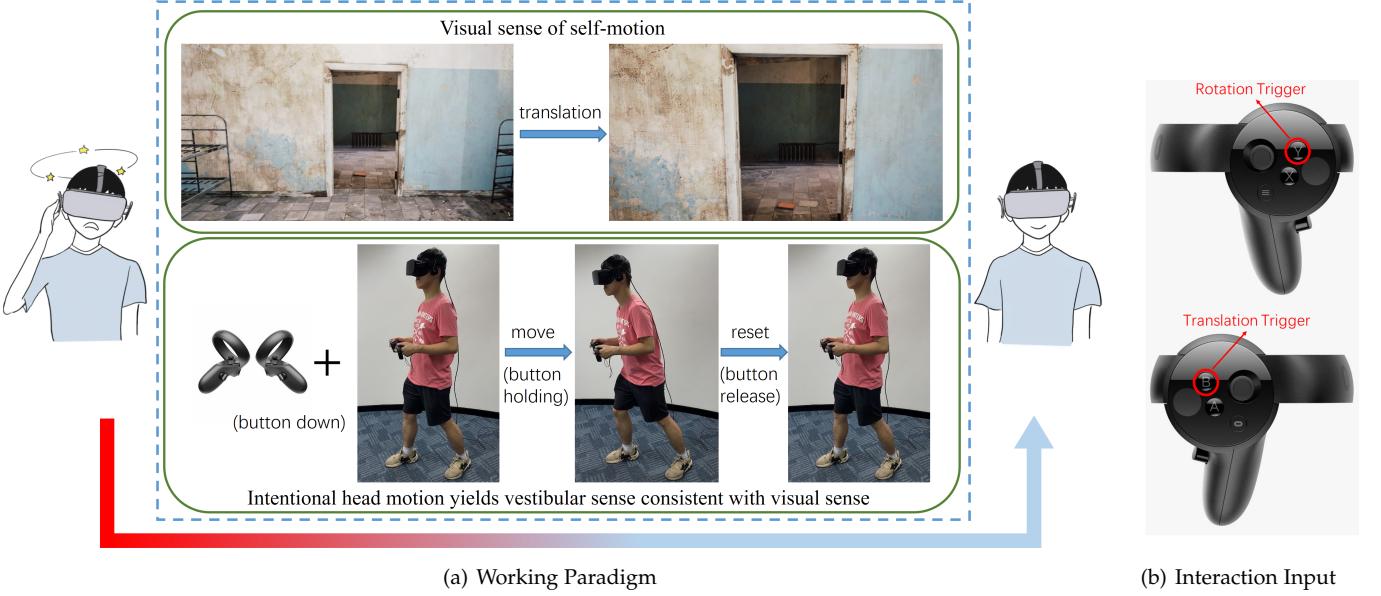
Fig. 1: (a) Working paradigm of our intentional head-motion assisted locomotion technique. When navigating in a virtual world (upper-middle), our method can significantly reduce cybersickness through an intentional movement of head and body (lower-middle) simultaneously in the coherent direction with the virtual world. (b) A pair of controllers are used as the input for interaction. Button 'B' on the right-hand controller is used for translation, and button 'Y' on the left-hand one is used for rotation.

body [21]. To study the cybersickness induced by varying translation velocities (also known as linear motion) and varying angular velocities using our locomotion technique, we conducted Experiment 1 and Experiment 2, respectively. Our results show a new finding different from the common conclusions in literature obtained without intentional head-motion assistance. We conducted Experiment 3 to compare our method with two other well-known methods: joystick-based steering (JS) and teleportation (TP) in terms of sickness, presence, and experience. It turned out that our approach can reduce cybersickness significantly when compared with JS, and can bring more presence when compared with TP. Consequently, our method enables users to navigate in the VEs freely without any auxiliary equipment except a commercially available HMD suite, Fig. 1(a) illustrates our approach's workflow, taking forward translation as an example using intentional head motion assistance.

To summarize, our main contributions include:

- We propose a novel locomotion technique with the assistance of intentional head motion, which yields low cybersickness while maintaining a high presence.
- We reveal some relations between translation/angular velocity and cybersickness through user studies on cybersickness, and they all present a possible U-shaped relation.
- We validate our method's effectiveness through user studies, and the results demonstrate that our method can be a feasible locomotion solution to VR applications using the commercially available HMD suite only.

2 RELATED WORK

In this section, we start from the fundamental of cybersickness and then survey different locomotion techniques with relevant issues about locomotion velocity.

2.1 Cybersickness and Alleviation

The most common explanation of motion sickness is the sensory conflict theory [16]. According to this theory, when the perceived information from different senses conflicts with each other or conflicts with the user's expectation, the user will feel sick [22]. The conflict between visually induced self-motion illusion (vection) and vestibular perception in a virtual environment is considered to be the main cause of cybersickness [2]. Another widely accepted view is postural instability theory, which considers that prolonged postural instability (uncontrolled movement) results in cybersickness [23], [24]. Other well-known theories include rest frame theory [25] and poison theory [26].

Some techniques have been proposed to alleviate cybersickness. Fernandes et al. [27] shrank the field of view (FOV), while Porcino et al. [28] tried to reduce cybersickness by reducing blur level and improving focus speed. Habgood et al. [29] proposed a node-based navigation system that allows the player to move between predefined node positions. Buhler et al. [30] utilized peripheral visual effects to reduce cybersickness. Liu et al. [31] utilized padded swing arms that lightly tap the head when users walk to provide haptic cues. Peng et al. [32] used two vibration motors on the left and right sides of the user's head to provide vibrotactile feedback to reduce cybersickness while improving presence. Compared with these methods, we aim at developing a method that neither changes the visual sense [27], [28],

[30] nor introduces additional vibration feedback [31], [32], and can navigate freely without restrictions like predefined nodes [29].

2.2 Locomotion Techniques

Real walking is the most natural and comfortable navigation way in VR. However, since the available space is often limited in reality, locomotion techniques are necessary to help users explore a larger virtual space.

In addition to the most commonly-used locomotion techniques like joystick-based steering and teleportation [16], walking-based locomotion methods via step-like movement are also widely investigated [33], which include treadmill walking [3], [34], walking-in-place (WIP) [4], [5], [35], [36], [37] and redirected walking (RW) [38], [39], [40]. Omnidirectional treadmills [3] enable locomotion in a wide range of VR space. Besides its limited commercial availability, the major limitation of treadmill walking is that it limits freedom of movement, since some belts are tied to the user, hindering the user from squatting down or doing other unexpected movements. User's motion cueing can enhance self-motion perception (vection illusion) in virtual reality [41], which explains some users' preference for WIP. WIP techniques have some variants that are based on other gestures [33] or only require head tracking data [42], [43], but WIP generally requires additional equipment to track the user's feet or leg, and may still result in an increased cybersickness [4]. RW exploits human perceptual mechanisms and manipulates the walking user's physical path to keep them inside the tracking space [38]. RW with distractors in the VE that distract the users can achieve a performance no worse than real walking [44]. Generally, RW requires a larger walking space (at least room-scale) to achieve the best performance [12], [13], [14], [15], [45], [46], [47].

Some leaning-based locomotion techniques [48], [49] were developed based on detecting the tilting of the head [9] or detecting weight shifting via Wii Balance Board [50] or user-powered chair [51], NaviBoard and NaviChair [52] to translate towards the expected direction. These techniques also require auxiliary equipment [50], [53]. There are some movement-boosting locomotion techniques, such as scaling the motion [10], translational gain [54], [55], and LazyNav [56]. Studies found that upper body leaning has a positive effect on self-motion perception [57]. However, in principle, self-motion perception by leaning may still conflict with vestibular perception. Therefore, leaning-based locomotions do not necessarily reduce cybersickness. Some studies reported that the cybersickness can be reduced when using extra equipment like NaviBoard or NaviChair [52], [58] while others reported that leaning-based locomotion techniques have almost the same level of cybersickness as JS or WIP [8], [9]. Some even reported that leaning-based techniques have a significant increment of cybersickness when compared with JS [10]. Both steering locomotion and TP have universal applicability in immersive VR. Clifton and Palmisano made comparisons between steering locomotion and TP [2] and found that steering was more sickening on average than TP. Langbehn et al. [59] also found that JS has a significant effect on cybersickness when compared with TP. Boletsis et al. [7] found that TP (an improved

version called dash) has a relatively low presence due to the "jump" of the view and immersion breaking. Kitson et al. [6] compared JS with four other motion cueing interfaces including NaviChair (stool with springs), MuvMan (sit/stand active stool), Head-Directed (Oculus Rift DK2), and Swivel Chair (everyday office chair with leaning capability). They found that JS is more comfortable and precise due to the reduced perceived control ability and the motion cueing interface's safety. Hashemian et al. [53] also compared JS with real-rotation, Swivel-Chair, and NaviChair. The result did not show significant differences in various aspects (including cybersickness) between these three techniques and JS. Recently, Buttussi et al. also confirmed that leaning-based locomotion does not differ with JS or WIP in terms of cybersickness [8]. Through the above comparisons, to develop a locomotion technique that can preserve high presence while reducing the cybersickness is worth studying.

2.3 Cybersickness and Locomotion Velocity

Many parameters during locomotion may influence the level of cybersickness in virtual reality [60]. Only a few works considered the influence from acceleration in locomotion [61], [62]. Particularly, acceleration can be a bigger contributor to cybersickness than other factors because of a strong induced vection [62], and cybersickness can be reduced by controlling accelerations [63].

Nevertheless, more researches investigated the correlations between cybersickness and locomotion velocity rather than acceleration/deceleration. So et al. [64] studied the effect of different velocities on cybersickness using joystick-based steering. They found that the translational velocity can affect the degree of cybersickness. Generally, faster translation or rotation was assumed to induce stronger cybersickness. Other studies also drew similar conclusions [65], [66]. Liu and Uang [67] studied the effect of different angular velocities on cybersickness and reported that a significant difference occurs within a range of $15°/s - 60°/s$ wherein the cybersickness increases with the increment of velocity. However, when the speed is too fast, cybersickness seems to decrease [16], [64], [67]. So et al. [66] proposed a metric called "spatial velocity" that combines speed and scene complexity to predict cybersickness levels. They found a strong positive correlation between spatial velocity and the level of cybersickness. As a newly proposed method, the effect of different velocities on cybersickness under the consistent head/body-motion assistance is worthy of investigation.

3 HEAD-MOTION ASSISTED LOCOMOTION

Sensory conflict theory indicates that cybersickness can be alleviated when the discrepancy between visual sense and vestibular sense is reduced [22]. However, a complete consistency between visual and vestibular cues is not necessary to help induce sickness-free self-motion [20]. Based on these principles, our method makes the head (wherein the vestibular system is located) intentionally move to reduce visual-vestibular conflicts and consistently links the motion cue between the virtual world and physical world, i.e., using intentional head motion to assist the locomotion in the VEs.

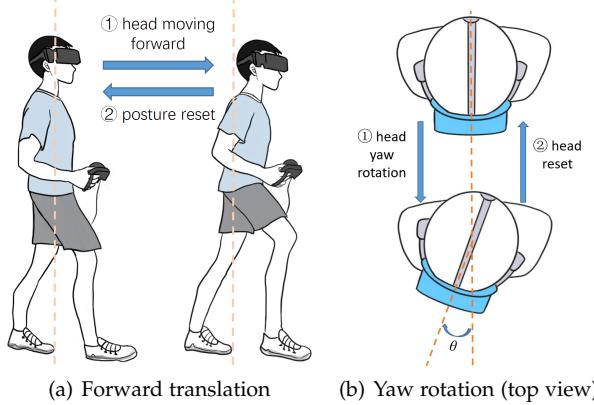(a) Forward translation   (b) Yaw rotation (top view)

Fig. 2: Illustration of intentional head motion used in our locomotion technique, taking forward translation (a) and yaw rotation (b) as examples. To complete a locomotion, our intentional head motion involves two stages: moving/turning and reset.

Specifically, the *head motion* refers to the head's translational movement or yaw rotation relative to the ground in a broad sense while not the relative movement to the torso only. During the translation locomotion, a user's torso and head move together whilst the feet can be nearly fixed. During the rotation locomotion, a user can turn his head while the torso stays almost stationary.

3.1 Locomotion Method

Our method provides two functions: translation and rotation. In a VR system, only when the user presses down and holds the specified buttons on the controllers, our locomotion scheme will be activated. Otherwise, the build-in physical locomotion will take effect automatically. Our method operates in the following steps:

1) Start: Press and hold the trigger button down to activate our locomotion scheme and start a locomotion event. Specifically, button 'B' on the right-hand controller is used to trigger translation, and button 'Y' on the left-hand controller is used to trigger rotation, as shown in Fig. 1(b).

2) Moving/Turning stage: In our system, we provide four directions of translation (i.e., forward, backward, leftward, and rightward) and two directions of yaw rotation (i.e., clockwise, counter-clockwise). Considering a target for moving in the virtual world, the user intentionally moves or turns his/her head physically in the direction consistent with this target; our run-time system records the HMD's position and orientation each frame, and when the system detects that the HMD's motion exceeds the specified thresholds (e.g., in our experiment, $8cm/s$ for translation, and $30°/s$ for yaw rotation, respectively), an enhanced self-movement in the VEs takes place with an instantaneous acceleration. The acceleration direction is the one closest to the physical direction from the provided four directions (forward, backward, left, and right). Once

the physical movement stops, the self-motion in the VEs will stop instantly.

3) Reset stage: The user releases the trigger button to deactivate our locomotion method and reset his/her posture during this interval for the next locomotion event, i.e., to restore the head's natural upright state physically. For instance, the backward head motion should be performed to reset from the forward translation; counter-clockwise yaw rotation should be performed to reset from the clockwise rotation.

Our intentional head-motion assisted locomotion is illustrated in Fig. 2. From the above step of locomotion, proprioception from self-motion is always matched to the efferent copy (neural equivalent to expectation) of the physical motion commands since the locomotion event is triggered and performed actively by the user. Using the steps described above, one locomotion event can be performed in about 1 – 2 seconds. If a user expects to move over a long distance, he/she can repeat this locomotion event multiple times.

An action of moving the head/body may make the body slant, therefore, we recommend that users operate the locomotion technique in a comfortable manner to keep balance, i.e., standing in a slight bow stance (Fig. 2 (a)), and then moving their upper body and head slightly forward/backward/leftward/rightward while keeping their feet stay almost stationary. During this process (moving and reset), the body's weight shifts between the left and right feet through simple body coordination, enhancing postural stability when performing the locomotion. Our method provides a flexible solution to navigation in the VEs. By combining multiple operations, the user can move to any place in the virtual world while the user's location in the physical world remains almost unchanged, i.e., a very small space that can accommodate a single person standing is enough. More details can be found in the demo video in the supplemental material.

3.2 Our Method vs. Leaning-based Method

Our method and leaning-based locomotion both relate to the tilt of the body or head. We manifest their differences in the following aspects. Firstly, these two methods work in a different scheme. Leaning-based interfaces are like using the body (e.g., the torso) as a joystick [6]. Thus, the user can keep a static position and virtual movement will still occur. In our approach, the gesture is more like swiping to generate a virtual movement because the virtual movement only occurs when the gesture is performed. Secondly, they have different effects on cybersickness based on their mechanism. Visual-vestibular conflict may be induced during locomotion by leaning-based methods. If taking the forward translation as an example, the whole body should follow the "start" – "leaning forward" – "keep leaning" procedure when a user launches leaning-based locomotion. The transition from start-leaning to keep-slanting yields a backward acceleration cue from the vestibular system, but the visual self-motion in the VE keeps unchanged. This conflict may elicit the same level cybersickness as JS [6], [8]. On the contrary, the user's visual and vestibular cues of self-motion using our method are always consistent.

(a) Urban with guiding path

(b) Screenshot of (a)

(c) Building with guiding path
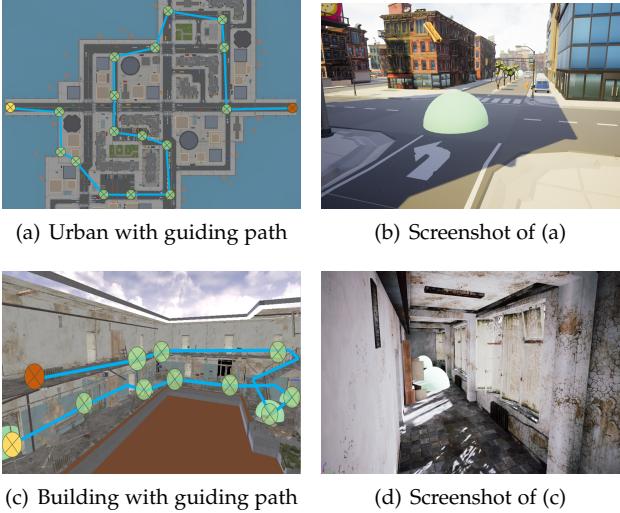

(d) Screenshot of (c)

Fig. 3: Two types of test scenarios: outdoor (a) and indoor (c). The indoor scene is a two-story building with a stairway connection. The blue lines indicate the route.

Finally, extra devices (e.g., balance board, chair, human-scale joystick, etc. [6]) are generally required to facilitate taking a leaning posture. While our method only employs the standard controller of a VR suite and is more generic.

4 EXPERIMENT DESIGN

4.1 Experiment Overview

Since cybersickness generally results from a discrepancy between visual and vestibular senses during locomotion, we firstly designed two separate experiments to investigate the cybersickness induced by these two types of locomotion behaviors (translation and rotation) with different velocities, i.e., translation velocities (Sec. 5) and angular velocities (Sec. 6) respectively. Secondly, we designed an experiment to compare our method with other popular locomotion methods using the commercially available HMD suite (Sec. 7). A threshold of significance $p = .05$ was set for all tests. All these experiment designs and procedures conform to the policy of the ethics committee at our university.

4.2 Apparatus and Setting

Apparatus used in the experiments is Oculus Rift (immersive VR headset with controllers for user interaction, FOV: 110 degrees diagonal, resolution: 1080×1200 per eye). Our experiments were conducted on a Windows platform with an Intel(R) Core(TM) i7-10875H @ 2.30GHz CPU and an NVIDIA GeForce RTX 1080 GPU. Our locomotion technique was developed based on the Unreal 4 engine.

4.3 Materials

We used three questionnaires, i.e., Simulator Sickness Questionnaire (SSQ) [68], Igroup Presence Questionnaire (IPQ) [69], and a user experience questionnaire designed by us. The SSQ questionnaire compromises 16 items of symptoms rated on 4-point scales (ranging from 0 to 3). It is used to measure nausea, oculomotor, and disorientation,

respectively, and also the total score can be obtained accordingly. The higher the score is, the more severe the simulator sickness is. IPQ is a scale for measuring the sense of presence in VEs, comprising 14 items rated on a 7-point Likert scale ranging from 0 to 6. IPQ has one general item (PRES, general sense of being there) and three subscales: spatial presence (SP, sense of physical presence), involvement (INV, the attention devoted to the VE), and experienced realism (REAL, the subjective experience of realism). The higher the IPQ score is, the more presence the participant reports. We processed these data in the same way as H. Regenbrecht and T. Schubert [69]. The user experience questionnaire contains seven items: comfort, ease of use, precise control, spatial orientation, enjoyment, problems, and overall evaluation, each ranging from -5 to +5 indicating from strong disagreement to strong agreement. The experience questionnaire is shown in the Appendix. Only SSQ is used for Experiment 1 and 2. All questionnaires are used for Experiment 3.

5 EXPERIMENT 1: TRANSLATIONAL VELOCITY

We conducted a within-group experiment to study the cybersickness induced by varying translational velocities using our locomotion technique. Two sub-experiments are included: *task-driven* sub-experiment (i.e., all users completed the same task regardless of their different exposure durations); and *exposure-driven* sub-experiment (i.e., all users were forced to undergo the same exposure durations). The two experiments used different participants, with a total of 75 participants took part in Experiment 1.

5.1 Task-driven Sub-experiment

We first conducted a *task-driven* experiment with varying translation velocities, i.e., each participant is assigned to complete the same task but with different parameters (translation velocities).

5.1.1 Participants

We recruited 40 participants (21 male, 19 female, ages $20 - 45$, including 18 undergraduates, 21 graduate students, and one professor). Each participant reported normal or corrected-to-normal vision with the good physical and psychological state, i.e., no fatigue or sickness.

5.1.2 Procedure

According to the task-driven experiment designs for evaluating cybersickness [6], [8], our experiment procedure is as follows. First, all the participants filled out the pre-test SSQ. Each item of the SSQ should be zero indicating no any symptoms, otherwise the participant was not qualified to complete this experiment. Next, the experimenter trained each participant on operating the right-hand controller with specified buttons and steering locomotion, as described in Sec. 3.1. Then the participant put on the HMD and practiced in a training scene, as shown in the Appendix. After we got the confirmation from the participants that they had mastered the translation locomotion (most users mastered it within 5 minutes), they took a break. The experiment started if the participant reported no symptoms and was ready, i.e., each item of the SSQ should be reported to zero.

TABLE 1: Cybersickness and preference in task-driven sub-experiment of Experiment 1, presenting mean value (M) and standard deviation (SD). Participants have the weakest cybersickness at $20m/s$ and favor $30m/s$ most on average.

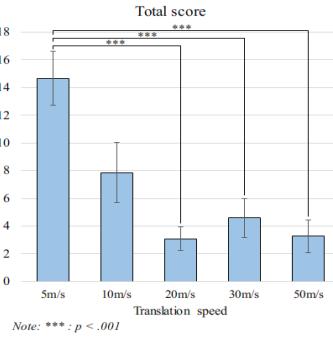| velocity		Nausea	Oculomotor	Disorientation	Total	Preference
5m/s	M	10.49	14.02	13.57	14.68	4.85
	SD	11.79	11.20	17.41	12.37	0.43
10m/s	M	6.44	6.44	8.00	7.85	3.60
	SD	9.99	10.09	21.35	13.70	0.71
20m/s	M	3.10	2.46	2.44	3.09	2.10
	SD	5.87	4.97	6.97	5.48	0.90
30m/s	M	3.82	3.60	4.87	4.58	1.85
	SD	8.03	7.48	11.60	8.86	0.83
50m/s	M	2.62	2.46	3.83	3.27	2.60
	SD	6.48	5.79	11.36	7.39	1.35

Fig. 4: Mean SSQ total scores in task-driven sub-experiment of Experiment 1 at different translation velocities. Error bars represent standard errors. The higher the total score, the higher the degree of sickness.

In this experiment, left-hand controller was not available to the users and the users would not learn the rotation method.

In the experiment, the participant was asked to navigate an urban scene (Fig. 3b) and play a checkpoint game as the task. We placed some green balls (checkpoints) in the scene and asked all participants to follow the same route according to the signpost (i.e., an arrow indicator on the ground), and the participants should hit all checkpoints in turn (Fig. 3 (a)). After the above test, the participants took a rest with no less than 5 minutes. They would not proceed to the next step until they got recovery, i.e., they should have no symptoms with each item of the SSQ reported to zero. Each participant repeated the above test five times to complete the same task but with different translation velocities each time, i.e., 5m/s, 10m/s, 20m/s, 30m/s, and 50m/s, based on the range indicated in [64]. The order of different translation velocities was randomly assigned to each participant, and counterbalancing was used to control the order effect of this experiment.

Participants filled out the SSQ questionnaire during the break. During each break, we also asked the participants to report their preferences with five different translation velocities using ordinal ranking. Specifically, the most favorite one is assigned the value of 1, the least favorite is assigned the value of 5, and the others are assigned in order according to their preferences.

5.1.3 Result

To complete the same task with the different velocities at $5m/s$, $10m/s$, $20m/s$, $30m/s$, and $50m/s$, the time cost of each task on average is around 350s, 190s, 130s, 100s, and 80s, respectively. Table 1 shows the average SSQ scores at different velocities and their standard deviations. Since we have no prior hypotheses on the three sub-scales of SSQ, only statistical analysis on the total score was necessary. Shapiro-Wilk test indicates that the assumption of normality is violated. Therefore, we analyzed the data with a Friedman test, rather than a repeated-measures ANOVA. According to the 5% significance level, we find that the translational velocity significantly affects the total score ($\chi^2(4) = 55.309$, $p < .001$). Dunn-Bonferroni post hoc test shows that the total score at $20m/s$ ($p < .001$), $30m/s$ ($p < .001$), $50\ m/s$ ($p < .001$) are all significantly lower than that at $5m/s$, which indicates $5m/s$ induces significantly higher sickness than the other three, as shown in Fig. 4. The cybersickness between other pairs of velocities does not show a statistically significant difference.

For the preference, Shapiro-Wilk test shows that the assumption of normality is violated. Therefore, Friedman test is conducted, and the result shows a significant difference ($\chi^2(4) = 97.2$, $p < .001$), which indicates that the participants have a significant preference for different velocities. Dunn-Bonferroni post hoc tests show that participants favored all other velocities than the velocity at $5m/s$ (for $10m/s$, $p = .004$; for $20m/s$, $p < .001$; for $30m/s$, $p < .001$; for $50m/s$, $p < .001$). Besides, participants significantly prefer $20m/s$ than $10m/s$ ($p = .004$), prefer $30m/s$ than $10m/s$ ($p < .001$), prefer $50m/s$ than $10m/s$ ($p = .047$). The preference between other pairs of velocities does not show a statistically significant difference. As shown in Table 1, participants favor $30m/s$ most on average.

Cybersickness had been reported sexist in its effects [70]. We also conducted Mann-Whitney U test between male and female participants on their total scores. No statistically significant difference is found between different genders ($p = .138$ for $5m/s$, $p = .668$ for $10m/s$, $p = .728$ for $20m/s$, $p = .573$ for $30m/s$, $p = .893$ for $50m/s$), which is different from the common view about gender effect on cybersickness [70].

5.2 Exposure-driven Sub-experiment

Translational velocity and exposure duration may have confounded effect on cybersickness. To further validate the findings described in the task-driven sub-experiment, we also conducted an *exposure-driven* sub-experiment, i.e., each participant is assigned to experiment with *equal-exposure* duration but with different parameters (translation velocities). Many studies conclude that 5 – 10 minutes of exposure is appropriate for eliciting sickness [29], [32], so we set 7 minutes of exposure for each task (i.e., a total of 35 minutes neither the time of practice is included nor the time of taking rest is counted).

5.2.1 Design and Participants

35 new participants (21 male, 14 female, ages 18 – 23, including 28 undergraduates and 7 graduate students) were enrolled in this experiment. None of them took part in the

TABLE 2: Cybersickness and preference in the exposure-driven sub-experiment in Experiment 1, presenting mean value (M) and standard deviation (SD). Participants have the weakest cybersickness at $20m/s$ and favor $20m/s$ most on average.

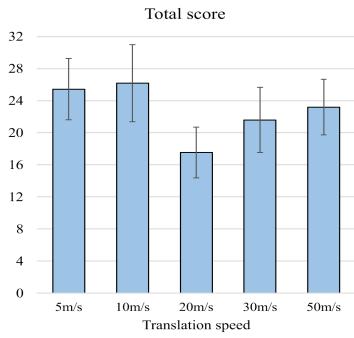| velocity		Nausea	Oculomotor	Disorientation	Total	Preference
5m/s	M	20.99	20.57	26.25	25.43	4.40
	SD	24.46	17.88	26.32	22.56	1.17
10m/s	M	23.44	18.19	29.83	26.18	3.51
	SD	27.99	19.12	35.75	28.44	1.01
20m/s	M	16.90	12.34	17.90	17.52	2.29
	SD	20.05	13.89	20.97	18.76	0.79
30m/s	M	20.99	14.73	22.67	21.59	2.31
	SD	26.36	16.33	27.45	23.98	1.18
50m/s	M	22.35	16.03	24.26	23.19	2.49
	SD	21.57	13.97	26.87	20.54	1.52

Fig. 5: Mean SSQ total scores in the exposure-driven sub-experiment in Experiment 1 at different translation velocities. Error bars represent standard errors. The higher the total score, the higher the degree of sickness.

task-driven sub-experiment in Experiment 1. Each participant reported normal or corrected-to-normal vision with a good physical and psychological state. The procedure of this exposure-driven sub-experiment is similar to task-driven sub-experiment except that the user can navigate freely to approach randomly-placed checkpoints as many as possible until 7 minutes have been consumed.

5.2.2 Result

Table 2 shows the average SSQ scores at different velocities and their standard deviations. Similarly, only statistical analysis on the total score is necessary. Shapiro-Wilk test indicates that the assumption of normality is violated. There is no significant difference on the total score among the five translation velocities (based on Friedman test, $\chi^2(4) = 8.839$, $p = .065$). As shown in Fig. 5, although no statistically significant result is found, the overall tendency suggests that the participants suffered the least cybersickness at $20m/s$.

For the preference, Shapiro-Wilk test shows that the assumption of normality is violated. Therefore, Friedman test is necessary, and the test result shows a significant difference ($\chi^2(4) = 48.571$, $p < .001$), which indicates that the participants have a significant preference for different velocities. Dunn-Bonferroni post hoc tests shows that, apart from $10m/s$, participants favored all other velocities than $5m/s$ ($p < .001$ for $20m/s$, $30m/s$ and $50m/s$). Also, partic-

ipants favored $20m/s$ ($p < .001$) and $30m/s$ ($p = .015$) than $10m/s$. The differences of preference between other pairs of velocities do not show a statistical significance.

We conducted Mann-Whitney U test between male and female participants on their total scores. Female participants experienced more severe cybersickness than male participants on average, but no statistically significant difference is found ($p = .263$ for $5m/s$, $p = .135$ for $10m/s$, $p = .083$ for $20m/s$, $p = .359$ for $30m/s$, $p = .154$ for $50m/s$).

5.3 Analysis and Discussion

In the task-driven sub-experiment, although the translational velocity affects cybersickness using our method, the post hoc tests show that the effect is significant only when comparing $5m/s$ with other velocities. Therefore, the cybersickness induced by our technique shows a different trend from the argument that faster velocity generally induces stronger cybersickness [64]. We infer a possible U-shaped relation between the translational velocity and the cybersickness degree under the intentional head-motion assistance. In the post interview, some participants reported that they felt sick very soon when the velocity was set to $5m/s$, and complained that the speed is too slow and lower than what they expected. This is also consistent with the motion sickness theory suggesting that the discrepancy between expectation of speed and the actual visual cues from self-motion may result in motion sickness [18].

For preference, $5m/s$ and $10m/s$ get the least favorites from the participants while the participants favored $20m/s$ and $30m/s$ most. This is not surprising since $20m/s$ induces the least cybersickness, and $30m/s$ does as well. In the post interview, some participants complained that $5m/s$ was too slow to quickly get them to the desired location. Most participants indicated that the higher velocity did not induce more sickness. However, they collided more easily with objects (e.g., lamp post, tree, car, etc.) at a higher speed and this would cause discomfort if they were not yet proficient in steering using our method. When a participant collided with virtual objects, his visual self-motion would stop suddenly whilst his head kept moving for a short while due to the inertia. This discrepancy between the vestibular sense and visual sense may explain to some extent why cybersickness is aggravated at higher speeds. As a result, they generally thought they could precisely control their translation at $20m/s$ and $30m/s$; and the least cybersickness can almost be obtained at the medium velocity.

On the whole, the results of the exposure-driven sub-experiment are consistent with the results from the task-driven sub-experiment. With the equal exposure duration, the level of cybersickness will not increase along with the increment of velocity under the assistance of intentional head motion. Similar to the task-driven sub-experiment, we still can conclude that the medium velocity is better (indicated in a U shape), both in the level of induced cybersickness and the participants' subjective preference.

In principle, vestibular feedback is provided for acceleration/deceleration but not for velocity in general. A constant locomotion velocity would not induce acceleration/deceleration perception from visual sensations. Therefore, it does not produce a mismatch between vestibular and
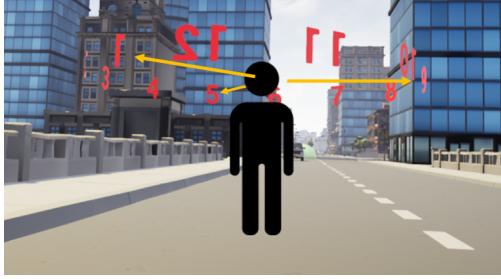
Fig. 6: Illustration of Experiment 2. the participants were asked to turn to some given numbers (i.e., orientations) in sequence using our method by only turning their heads.

TABLE 3: Cybersickness and preference in Experiment 2, presenting mean value and standard deviation.

velocity		Nausea	Oculomotor	Disorientation	Total	Preference
$30°/s$	M	5.25	6.06	5.22	6.45	4.83
	SD	8.63	10.18	8.74	9.12	0.59
$60°/s$	M	2.62	2.84	3.48	3.37	3.68
	SD	6.48	5.61	10.81	7.28	0.76
$90°/s$	M	0	0.57	1.04	0.56	2.60
	SD	0	2.65	3.71	1.60	0.98
$120°/s$	M	0.95	1.52	2.09	1.68	2.28
	SD	4.73	5.21	6.72	5.35	0.88
$180°/s$	M	0.48	1.14	1.04	1.03	1.58
	SD	2.11	4.39	3.71	3.17	0.90

visual perception when no vestibular feedback is detected. However, the two sensations do not always match in a locomotion event, even with constant velocity. To be specific, one locomotion event includes three phases: start, running, and stop, wherein both the start and stop phases induce acceleration/deceleration in visual sensations. Therefore, the discrepancy between vestibular and visual sensation is prone to occur in these two phases due to the absence of vestibular feedback from acceleration/deceleration. Exactly, our locomotion technique evokes a vestibular perception by intentional head motion to match the acceleration/deceleration of visual sensations during start and stop, which can help reduce the cybersickness. Our results provide an clue that the discrepancy between visual and vestibular feedback is expected to have an effect on cybersickness whilst actual amount of velocity is not expected to have an effect on cybersickness.

6 EXPERIMENT 2: ANGULAR VELOCITY

We conducted a within-group experiment to study the cybersickness induced by different angular velocities using our method. The same participants with task-driven sub-experiment of Experiment 1 (i.e., 40 participants described in Sec. 5.1.1) all took part in this experiment after they completed the task-driven sub-experiment and got recovery. Each participant confirmed himself/herself recovered to a normal state and was capable of performing this test, i.e., each item of SSQ should be reported to be zero. To perform Experiment 2, each participant was firstly trained to master our rotation locomotion technique, as described in Sec. 3.1 by turning one's head meantime pressing and then holding the 'Y' button on a left-hand controller. In Experiment 1 and Experiment 2, these re-use participants underwent different training procedures, manipulated different controllers in different manners. Their head behaviors are distinct from each other to complete different locomotion tasks. From many aspects, these two experiments were sufficiently different to not threaten the validity of our study.

6.1 Procedure

An urban architectural scene is used for this experiment, wherein a user is surrounded by 12 numbers to indicate the orientation (like a virtual clock, as shown in Fig. 6). In this experiment, the participants were asked to turn to a series of orientations (e.g., 12 o'clock, 5 o'clock, 9 o'clock, etc.) correctly by our rotation approach under the experimenter's

verbal instructions. Both clockwise/counterclockwise rotations are available for the user, and can be used freely according to their own preferences.

A total of velocities at $30°/s$, $60°/s$, $90°/s$, $120°/s$, $180°/s$ were used according to the analysis in [67]. Each participant repeated the test as mentioned above five times with different levels of angular velocities. The order of different angular velocities was randomly assigned to each participant, and counterbalancing was used to control the order effect. Each test lasts for 3 minutes. After each test, the participants took at least 5 minutes to rest until they recovered, i.e., they had no symptoms and were ready to proceed to the next event, with each item of the SSQ being reported to zero. Participants filled out the SSQ at each break. We asked the participants to report their preferences of the five different angular velocities using ordinal ranking, i.e., the most favorite one is assigned a value of 1, the least favorite is assigned a value of 5, and the others are assigned in order according to their preferences. The workflow follows the same way with Experiment 1, as described in Sec. 5.1.2.

6.2 Result

We used the same statistical methods with correction as described in Sec. 5.1.3. Participants' SSQ scores are listed in Table 3. Shapiro-Wilk test indicates that the assumption of normality is violated. Friedman test detects significant difference among different angular velocities in terms of the total score ($\chi^2(4) = 24.235$, $p < .001$). Dunn-Bonferroni post hoc test shows that the total score at $90°/s$ is significantly lower than that at $30°/s$ ($p = .047$), which indicates $30°/s$ elicits significantly higher sickness than $90°/s$. According to Fig. 7, the total score indicates that participants experienced the slightest sickness at a medium velocity $90°/s$, and this indicates a possible U-shaped relation between the level of cybersickness and angular velocity.

As to the preference, Shapiro-Wilk test indicates that the assumption of normality is violated. Friedman test indicates the significant difference ($\chi^2(4) = 105.166$, $p < .001$) among the different velocities. Dunn-Bonferroni post hoc tests show that participants significantly prefer $60°/s$ ($p = .013$), $90°/s$ ($p < .001$), $120°/s$ ($p < .001$), and $180°/s$ ($p < .001$) to $30°/s$. Also, participants prefer $90°/s$ ($p = .019$), $120°/s$ ($p = .001$) and $180°/s$ ($p < .001$) significantly to $60°/s$. Besides, $180°/s$ is significantly more favorable than $90°/s$ ($p = .037$). The
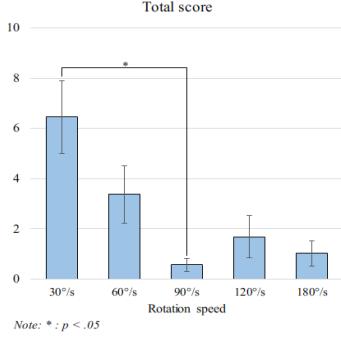
Fig. 7: Mean SSQ total scores in Experiment 2 at different angular velocities. Error bars represent standard errors. The higher the total score, the higher the level of sickness. Participants experienced significantly more severe sickness using $30°/s$ than using $90°/s$.

TABLE 4: Cybersickness in an additional experiment using joystick-based steering.

velocity		Nausea	Oculomotor	Disorientation	Total
$30°/s$	M	32.96	29.63	48.09	40.46
	SD	34.76	27.84	46.32	37.47
$60°/s$	M	18.21	19.29	31.64	25.16
	SD	19.76	22.32	39.42	28.39
$90°/s$	M	19.95	19.98	34.17	26.86
	SD	21.53	22.30	39.55	29.54
$120°/s$	M	17.35	17.92	25.31	22.44
	SD	32.44	30.56	45.67	39.62
$180°/s$	M	11.27	12.40	25.31	17.34
	SD	18.99	20.42	40.26	28.00

result indicates that the participants favor $180°/s$ most and $30°/s$ least.

6.3 Additional Experiment on Angular Velocity Using JS locomotion

From Table 1 and Table 3, the overall sickness level in Experiment 2 seems to be lower than that in Experiment 1. One may suspect that the task is not sufficient to induce sickness within a limited time. To test whether our task is reasonable for eliciting sickness, we conducted an additional experiment and enrolled 11 new participants (all male graduates) to complete the *same* rotation task with Experiment 2 with even less exposure duration (around 2'35" on average) using the joystick-based steering locomotion rather than using our method, as shown in Table 4.

Shapiro-Wilk test indicates that the assumption of normality is violated. Therefore, we analyzed the total scores with Mann-Whitney U test to compare the two methods. As shown in Table 5, we found that the steering method elicits more severe cybersickness in all five velocities than our method with the same task. This demonstrates the validity of our task of Experiment 2.

6.4 Analysis and Discussion

In Experiment 2, the levels of sickness are relatively low. The angular velocity does not show a significant effect on cybersickness except that $30°/s$ induces more severe

TABLE 5: Mann-Whitney U test on the results of additional experiment in Table 4 . JS elicits significantly severe sickness in all five velocities.

velocity	$30°/s$	$60°/s$	$90°/s$	$120°/s$	$180°/s$
Mann-Whitney U	90	120.5	90	126	121
Z	-3.413	-2.927	-4.286	-3.172	-3.503
p	.001	.003	$< .001$	.002	$< .001$

sickness than $90°/s$ does. There is a tendency that the participants have more severe cybersickness at $30°/s$ on average. This is also incompatible with prior studies [64], [67] that conclude faster rotation generally induces stronger cybersickness within a specific range of velocity. The participants favor a medium velocity at $180°/s$ most and dislike $30°/s$ and $60°/s$. In the post interview, some participants complained that $30°/s$ and $60°/s$ were too slow to get them to the expected orientation.

7 EXPERIMENT 3: COMPARISON

We conducted an experiment to compare our method with the well-known locomotion techniques, i.e., joystick-based steering locomotion and teleportation.

7.1 Participants

We recruited 51 participants (33 male, 18 female, ages $19 - 45$). Each participant reported normal or corrected-to-normal vision with a good physical and psychological state. One male participant failed to complete this experiment due to heavy cybersickness, and a total of 50 samples are finally valid.

7.2 Procedure

Before the experiment, each user was asked to fill in the SSQ. Then the user performed the same task three times using three methods (our method vs. JS vs TP) in a randomized order, and counterbalancing was used to control the order effect. For each test, the users were first trained to master this translation technique in the training scene. After that, the users took off the HMD and rested until they confirmed themselves in a normal state, i.e., each item in the SSQ was reported to be zero.

Two types of test scenes were provided for each user at each test: an outdoor urban area and an indoor building, as shown in Fig. 3. Then they were asked to navigate through all checkpoints as in Experiment 1. They first completed the task in the outdoor scene, and then proceeded to test the indoor scene without any break. In the VEs, the translational velocity in the outdoor scene is set to $20m/s$, which is one of the user's favorite velocities with least cybersickness obtained from Experiment 1 (Sec. 6). The level of cybersickness is considered to be proportional to the product of the scene's complexity and the navigation velocity [66]. Based on the indoor scene's complexity measured is around four times of the outdoor scene's, we used an estimated velocity $5m/s$ for indoor scene according to the above rule, which could guarantee a similar level of overall cybersickness in both scenes under the same situation. In both scenes, the angular velocity was set to $180°/s$. All three locomotion techniques

used the same velocity configuration. The JS method was implemented using view-directed steering; neither acceleration nor deceleration was applied. The TP method was implemented by the Unreal engine's build-in function.

During the experiments, we used the Fast Motion Sickness Scale (FMS) [71], [72] to evaluate the temporal level of sickness through verbal report. This single-item verbal rating scale ranges sickness from 0 (no nausea) to 20 (extreme nausea) to quickly obtain participants' status every minute. With the help of FMS value, the experimenter can decide to terminate the experiment immediately once an FMS value reported above the threshold (generally 15). Throughout the experiment, only one male participant quit the experiment due to heavy sickness. FMS was designed as a simple and fast measure of nausea and general discomfort [71] with only a single item for temporal use. Hereby, we use verbal FMS as a criterion only to determine onsite whether to terminate the experiment or not. In fact, we did not record these temporal data and would not use them for the subsequent analysis because SSQ has covered more aspects of sickness.

After each test, the participants were asked to fill three questionnaires: SSQ, IPQ, and user experience. After the experiment, the participants were asked to give an ordinal rating of preference on all three methods. Specifically, the one they liked the most will be assigned a value = 1, the next favorite one will be assigned a value = 2, and the one they liked the least will be assigned a value = 3. Moreover, the participants were asked to wear a bracelet to measure the calorie burned during the test using our method. Besides, they were asked to complete an additional 5-point Likert questionnaire named adapted device assessment questionnaire (DAQ) [8], [73] to measure their fatigue.

7.3 Result

On average, the participants completed the task in $210s$ (using TP), $200s$ (using JS), and $260s$ (using our method, and the average calorie consumption measured is about 0.63 kCal), respectively. The descriptive statistical results for the whole post-test questionnaire is shown in Table 6 and Table 7.

For the SSQ total scores, Shapiro-Wilk test indicates the violation of normality in all four terms. A Friedman test was conducted and the result shows a significant difference ($\chi^2(2) = 37.115$, $p < .001$), which indicates that the participants experienced different levels of sickness when using these three methods. Dunn-Bonferroni post hoc test shows that the total scores from TP ($p < .001$) and our approach ($p = .002$) are significantly lower than that when using JS, which indicates that our approach and TP induce significantly less sickness than JS.

For IPQ and experience questionnaire, we conducted repeated-measures ANOVA with post hoc tests with Bonferroni correction on the items that produced normally distributed data, and Friedman tests with Dunn-Bonferroni post hoc tests on the items that are not normally distributed. As shown in Fig. 9, the participants feel significantly different levels of 'spatial presence' ($p = .039$) and 'experienced realism' ($p = .004$). Post hoc test indicates participants experienced higher 'spatial presence' from our method ($p = .041$)
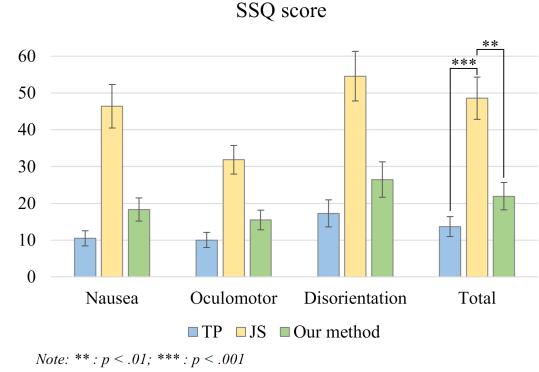

Fig. 8: Mean SSQ scores of teleportation vs. joystick-based steering vs. our method. Error bars represent standard errors. Participants have most severe sickness using JS.
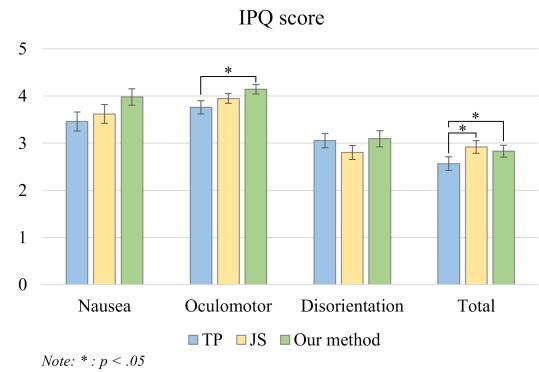

Fig. 9: Mean IPQ scores of teleportation vs. joystick-based steering vs. our method. Error bars represent standard errors. Our method can obtain higher presence than TP significantly.

than TP. Also, post hoc tests indicate higher 'experienced realism' from both JS ($p = .013$) and our method ($p = .021$) over that from TP. As to the 'general presence' and 'involvement', no significant difference can be found.

For preference, we conducted the Friedman test and found a significant difference ($\chi^2(2) = 9.120$, $p = .010$). Dunn-Bonferroni post hoc tests show that participants rate TP significantly higher than JS ($p = .008$). There is no significance in preference between our method and others. As shown in Table 6, participants prefer the TP method the most on average. Our method is also approved by some of the users and was selected as the best. The post interview indicated that those who choose our method often have higher demands for presence.

In terms of user experience, the analysis revealed statistically significant differences for comfort ($\chi^2(2) = 6.857$, $p = .032$), ease of use ($\chi^2(2) = 19.179$, $p < .001$), and precise control ($\chi^2(2) = 8.651$, $p = .013$), as shown in Table 7. Pairwise comparisons revealed more 'comfort' of TP than JS ($p = .049$), more 'ease of use' of TP than JS ($p = .049$), more 'ease of use' of TP than our method ($p < .001$), and more 'precise control' of 'TP' than 'JS' ($p = .018$). No other significant differences were found for spatial orientation, enjoyment, problems, and overall evaluation. Overall, in most respects, our approach is not significantly different from other approaches in terms of user experience.

TABLE 6: Results of cybersickness, presence and user preference in Experiment 3 with the format $M(SD)$, presenting mean value and standard deviation. Our method induces significantly less cybersickness and has higher presence.

	SSQ				IPQ				Preference
	Nausea	Oculomotor	Disorientation	Total	PRES	SP	INV	REAL	
TP	10.49(14.71)	10.01(14.56)	17.26(26.01)	13.69(19.00)	3.46(1.42)	3.76(0.98)	3.06(1.06)	2.57(1.02)	1.68(0.79)
JS	46.36(41.61)	31.84(27.52)	54.57(47.46)	48.55(40.48)	3.62(1.41)	3.95(0.72)	2.81(1.04)	2.92(0.95)	2.28(0.81)
Ours	18.32(22.46)	15.46(18.69)	26.45(34.24)	21.92(26.29)	3.98(1.22)	4.14(0.72)	3.10(1.20)	2.83(0.89)	2.04(0.75)

TABLE 7: User experience in Experiment 3 with the format $M(SD)$, presenting mean value and standard deviation. Higher scores represents better VR experience.

	Comfort	Ease of use	Precise control	Spatial orientation	Enjoyment	Problems	Overall
TP	1.50(2.78)	2.86(2.31)	1.60(2.32)	1.08(2.65)	1.48(2.52)	2.00(2.19)	2.00(2.04)
JS	0.14(2.60)	2.48(1.95)	0.08(2.43)	0.92(2.30)	0.96(2.35)	1.60(1.45)	1.18(2.20)
Ours	0.68(2.34)	1.30(2.46)	0.74(2.34)	1.42(2.43)	0.98(2.14)	2.12(2.12)	1.62(2.07)

7.4 Analysis and Discussion

In Experiment 3, we found that our method significantly reduces cybersickness (Sec. 7.3) compared with JS presumably because our method reduces visual-vestibular conflict. Besides, our method brings a significantly higher self-reported presence and realism than TP, as we expected. A few users reported high cybersickness when using our method, and we observed that some of these users' postures were wobbly, and their upper bodies were swaying in the left-right axis when they wanted to shift their weight forward/backward, which might be the main cause. This situation coincides exactly with the principle of postural instability theory [23], that is, an unstable posture may easily cause sickness. This reminds us that more efforts should be paid to helping users operate fluently by more detailed training.

It is very likely a higher level of presence could be elicited when the physical motion is consistent with the perception of self-motion in the VE. Our method shows significantly better performance over TP on items 'spatial presence' and 'experienced realism'. However, the item 'involvement' does not show significant difference. This may due to the fact that many amateur participants generally paid much attention to the physical coordination between the head motion and hand operation using the controller, thereby inducing less enjoyment with our method. We believe the sense of involvement and other items can be improved after the users get accustomed to our locomotion technique.

Our method shows the inferior result to TP only in the item 'ease of use'. In fact, many participants had prior experiences with VR, and they were more familiar with the operation of JS and TP. As a new way of steering locomotion, our method needs more efforts to grasp with head/body motion assistance rather than only using controllers by JS and TP.

Since head/body movement always accompanies an instance of locomotion in our method, a measure of the user's physical and mental workload is necessary. Table 8 shows the DAQ descriptive statistics results. The calorie burned (about 0.63 kCal) and the five items in DAQ measuring fatigue (finger, wrist, arm, shoulder, and neck fatigue) suggest that fatigue is not an issue of our method. However, participants grade 'mental effort' relatively high

TABLE 8: Adapted Device Assessment Questionnaire results, presenting mean value and standard deviation. Symbol (+)/(-) denotes that a higher/lower value corresponds to better experience, respectively. Symbol (0) denotes that a value closer to the middle value (3) corresponds to better experience.

Item	Group Value $M(SD)$
Required force (-)	1.8 (0.8)
Smoothness during operation (+)	3.1 (0.7)
Mental effort (-)	2.6 (0.5)
Physical effort (-)	2.2 (0.7)
Difficulty to be accurate in movements (-)	2.5 (0.9)
Slowness in movement and rotation (0)	2.7 (0.5)
Finger fatigue (-)	1.2 (0.4)
Wrist fatigue (-)	1.1 (0.3)
Arm fatigue (-)	1.1 (0.3)
Shoulder fatigue (-)	1.1 (0.3)
Neck Fatigue (-)	1.5 (0.7)
General comfort (+)	3.9 (0.6)
Overall ease of use (+)	4.0 (0.5)

(=2.6, from Table 8). In all, we conclude that participants do not feel much physical fatigue, but have a somewhat mental workload. This is understandable because users should pay more attention to make synchronizing the intentional head motion and pressing/releasing the button frequently. In the post interview, no one reported that they felt physical fatigue after the experiment. Some participants like this way very much, thinking that our method with such slight physical motion can give them a certain degree of relaxation after a long period of studying. This is because the participants are college students and professors, who are often sedentary and lack sufficient exercise. However, they also consider that such a small amount of activity is not enough to make it a physical exercise consistent with the calorie result.

8 Conclusion, Limitation and Future Work

In this paper, we present a simple and efficient locomotion method through intentionally physical head motion to maximize the alignment of the visual and vestibular senses. A user study indicates that our method has less cybersickness than JS while achieving a high level of presence, which can be a feasible solution to navigation in VR games and applications. Furthermore, our quantitative analysis of the effects

of different velocities on the level of cybersickness induced may provide a valuable clue to design an appropriate speed for different VR games or applications.

Our method also has some limitations. In our locomotion system, the translational direction in VE is one of the four primary directions. Therefore, the direction of motion in the virtual world is not precisely consistent with the actual motion in the physical world. Therefore, we can explore the effect of the deviations caused by these approximations on the user's perception and its cybersickness level in the future. We find a possible U-shaped relation between different velocities and the cybersickness degree and provides an explanation based on general theories for this phenomenon. However, the underlying rationale still needs to be further explored and verified by experiment. Besides, our study does not include any quantitative measurement of hypothetical sensory conflict; evaluating predictions of the sensory conflict theory will be our future work.

To proficiently grasp our locomotion technique, the users must generally have good physical movement and coordination skills between the human hand, head, and body. Otherwise, they have to practice a lot. This requirement may lower the ease of use and usability of our method. In the future, we can try to predict users' movement intention by electroencephalography instead of holding and pressing a button, so that the ease of use can be improved in this way.

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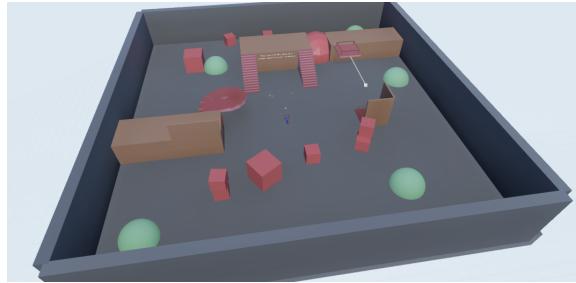
Fig. 10: The scene we used to train the participants to master different locomotion techniques.

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APPENDIX

User Experience Questionnaire

We design the user experience questionnaire as follows:

1) To what extent do you find this locomotion comfortable?
2) To what extent do you find this locomotion easy to use?
3) To what extent do you feel you have precise control when using this locomotion?
4) To what extent do you feel it easy to steer yourself in the desired direction in this locomotion?
5) To what extent do you enjoy this locomotion?
6) To what extent do you find this locomotion problematic?
7) What is your overall assessment of this locomotion?

Training Scenario

The scene used to train the participants is shown in Fig. 10, which includes both static and moving objects. The user should learn to avoid the collision from the moving objects.

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