Exploring Locomotion Methods with Upright Redirected Views for VR Users in Reclining & Lying Positions

Tianren Luo*
Institute of Software, Chinese Academy of Sciences
Beijing, China

Chenyang Cai
School of Information Technology, Beijing University of Technology
Beijing, China

Yiwen Zhao
School of Artificial Intelligence, Beijing Normal University
Beijing, China

Yachun Fan
School of Artificial Intelligence, Beijing Normal University
Beijing, China

Zhigeng Pan
College of Artificial Intelligence, Nanjing University of Information Science and Technology
Nanjing, Jiangsu, China

Teng Han†
hanteng@iscas.ac.cn
Institute of Software, Chinese Academy of Sciences
Beijing, China

Feng Tian*
Institute of Software, Chinese Academy of Sciences
Beijing, China

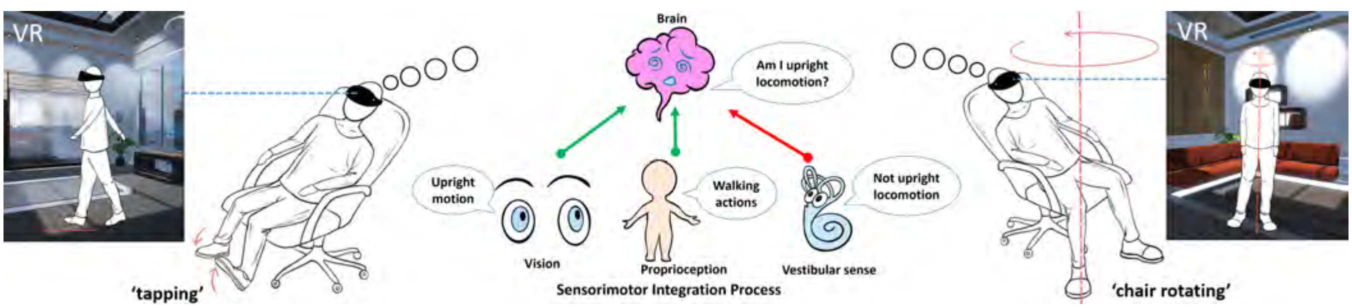


Figure 1: The illustrations of 'tapping' and 'chair rotating' as the most preferred locomotion methods for VR users with upright redirected views in reclining & lying positions, and the challenges of visual-vestibular-proprioceptive sensorimotor conflict

ABSTRACT

Using VR in reclining & lying positions is getting common for users, but upward views caused by posture have to be redirected to be parallel to the ground as when users are standing. This affects users' locomotion performances in VR due to potential physical restrictions, and the visual-vestibular-proprioceptive conflict. This paper is among the first to investigate the suited locomotion methods and how reclining & lying positions and redirection affect them in such conditions. A user-elicitation study was carried out to construct a set of locomotion methods based on users' preferences when they were in different reclining & lying positions. A second study developed user-preferred 'tapping' and 'chair rotating' gestures, by evaluating their performances at various body reclining angles, we measured the general impacts of posture and redirection. The results showed that these methods worked effectively, but exposed some shortcomings, and users performed worst at 45° reclining angles. Finally, four upgraded methods were designed and verified to improve the locomotion performances.

*Tianren Luo (e-mail: luotianren21@mails.ucas.ac.cn) is also with School of Computer Science and Technology, University of Chinese Academy of Sciences. Feng Tian is also with School of Artificial Intelligence, University of Chinese Academy of Sciences.
†Corresponding author.

UIST '23, October 29–November 01, 2023, San Francisco, CA, USA

ACM ISBN 979-8-4007-0132-0/23/10…$15.00
https://doi.org/10.1145/3586183.3606714

CCS CONCEPTS

• **Human-centered computing** → *HCI design and evaluation methods*; **Virtual reality**; User interface design.

KEYWORDS

virtual reality, locomotion techniques, redirection, sensory conflict

ACM Reference Format:

Tianren Luo, Chenyang Cai, Yiwen Zhao, Yachun Fan, Zhigeng Pan, Teng Han, and Feng Tian. 2023. Exploring Locomotion Methods with Upright Redirected Views for VR Users in Reclining & Lying Positions. In *The 36th*

Annual ACM Symposium on User Interface Software and Technology (UIST '23), October 29–November 01, 2023, San Francisco, CA, USA. ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3586183.3606714

1 INTRODUCTION

Designing engaging and efficient locomotion methods in VR is prominent, but challenging in various interaction circumstances. Recently, interacting with VR while users are in their reclining & lying positions has become a novel feature enabled by mainstream commercial devices and well perceived by the community [8, 88, 89]. The setting is described to be more relaxing ergonomically, avoid potential neck or back pain, and potentially extend the session time of VR users. Actually, it is not unusual to use VR in bed, sofa, or chairs for watching movies, playing games, having conferences, and even handling office work. Though promising, the laid-back mode is not necessarily efficient for interactions such as locomotion. First, compared with using VR standing and sitting, the reclining or lying position adds more physical constraints to users, opting out of many established locomotion actions or gestures (e.g., physical walking) that are considered easy and straightforward. Second, to configure the device while users are reclining or lying, the system shall upright redirect the views, i.e., rotate users' upward views to be parallel to the ground so that they can see virtual scenes in front (instead of the sky). The redirection adds extra sensorimotor conflicts to locomotion interactions due to the multi-sensory integration being disturbed [15, 16, 49, 58]. As a result, it is critical to look into proper locomotion methods in situations of users' reclining & lying positions to make the setup more practical.

VR locomotion methods' performances are usually measured by *perceptive metrics* (estimation of the moving distance and turning angle [6, 40]), *experiential metrics* (self-motion sensation [74], presence [62], motion sickness [17]), and *functional metrics* (accuracy/overshoot [30, 101], controllability [52], fatigue [2]). Good locomotion perceptive and experiential metrics rely on multi-sensory integration including vision [45], proprioception [19], and vestibular sense [3]. Effortless artificial locomotion methods (e.g., teleportation [12] and joystick [57, 77]) lack vestibular and proprioceptive stimulation and have been shown to result in low spatial awareness, self-motion sensation, and presence for users in their sitting and standing positions [5, 11, 50, 104]. Comparably, gestures-based embodied locomotion methods have been proven to be effective for users in sitting and standing cases, especially those that provide proprioceptive and/or vestibular stimulation following daily locomotion metaphors, e.g., chair swiveling [44], walking-in-place [51, 96], arm swinging [63], torso leaning [25, 103], etc. These often result in low cognitive load, good spatial awareness, and natural self-motion sensations, though at a cost of a certain physical effort [97, 104]. Inspired by the previous work, this paper looks into suited embodied locomotion methods when users are in their reclining & lying positions, with considerations of the function metrics, and special attention to users' perceptive and experiential metrics.

This paper is among the first to investigate suited locomotion methods with upright redirected views for VR users in their reclining & lying positions, and explore the general impact of such posture and redirection on their performances. The techniques shall conform to the reclining or lying setup, and reduce potential risks caused by the sensorimotor conflict due to upright redirection. To do so, we first performed a user-elicitation study to obtain user-preferred locomotion methods when they were at various reclining & lying conditions. Participants were provided with the standing locomotion views as references and asked to design locomotion methods appropriate to the conditions. In total, a set of 51 moving gestures and 50 turning gestures were proposed. Among them, 'tapping' to move and 'chair rotating' to turn were found the most suitable and preferred based on users' feedback.

In a second study, as 'tapping' and 'chair rotating' also represented many locomotion methods with typical sensorimotor stimulation and daily moving & turning metaphors, we implemented the two methods and took them as representative examples to measure the potential impact of body angle & redirection angle on locomotion performances. The results showed that the two locomotion methods worked effectively and were well-perceived by most participants in the reclining and lying conditions. It was found that these methods generally provided the worst perceptive and experiential metrics to the participants at 45° reclining position, and 0° sitting position performed the worst regarding functional metrics. In a final study, we improved the 'tapping' and 'chair rotating' based on the previous findings by reducing the negative effects of posture & sensory conflict. The outcomes of the evaluation highlighted improved locomotion performances of the upgraded methods.

This paper makes the following contributions: i) notion of challenges of locomotion in VR including physical constraints and sensorimotor conflicts while users are in their reclining & lying positions; ii) construction of a locomotion method set for VR users with upright redirected views in various reclining & lying conditions, and identification of features and preferences of user designs; iii) evaluation of the locomotion performances at different reclining angles using the 'tapping' and 'chair rotating' gestures, and analysis of the general impacts and causes of posture & redirection; and iv) design of 4 upgraded methods of 'tapping' and 'chair rotating' based on their shortcomings and the findings.

2 RELATED WORK

Our work is closely related to the design of locomotion methods in VR, including those considering various body postures' effects, and research on sensorimotor integration and conflict in VR.

2.1 Embodied Locomotion Methods in VR

Gesture interaction has been widely used in various aspects of VR and is considered natural [55, 59, 69]. Actions of various body parts are widely used as embodied locomotion gestures in 2-3 DoF's ground-based navigation [33, 67]. Human's arm/hand actions are common, fast, and accurate in daily life [35], thus these gestures are often used for VR locomotion methods. Typical arm/hand gestures include arm-swinging with walking metaphor [63], arm-cycling with swimming metaphor [14, 18], and other gestures without metaphors [37]. As we are used to use feet to move and turn in actual life, leg/foot gestures generally provide good self-motion sensation, presence, and spatial awareness through natural proprioceptive stimulation [97], especially with locomotion metaphors like walking [102], driving [56], etc. Moreover, locomotion gestures via some other body parts have also been shown to perform well if they can provide natural sensorimotor stimuli, e.g., head shaking [86], and head/torso tilt [25, 34, 103].

User-elicitation study is a simple and effective method to design user-friendly gestures, as it meets users' preferences well [95]. In recent years, many locomotion methods in VR were proposed by user-elicitation studies, such as gestures of mid-air arm/hand [60], walking-in-place [43], foot [24], and body [29], etc.

Various postures affect the performances of embodied locomotion methods. Standing position often induces the best perceptive & experiential metrics in VR locomotion, because it conforms to the daily sports posture and usually has natural multi-sensory stimulation. However, maintaining the balance and supporting the body could cause problems of fatigue, and affect users' stability and control accuracy [104]. The sitting position makes up for the shortcomings of the standing position, but its self-motion sensation is weaker [104]. However, few studies have been done on how the reclining & lying positions affect the performances of embodied locomotion methods, especially when upright redirection is applied.

The exploration of locomotion methods in users' reclining & lying positions is built upon these prior knowledge. Following a similar approach, a user-elicitation study is used in Study 1 to elicit suitable gestures for embodied locomotion when users are in their reclining & lying positions.

2.2 Sensorimotor Integration & Conflict

Human locomotion is often accompanied by a complex sensory integration process [9]. In this process, visual, vestibular, and proprioceptive signals get dynamically-different weights from the brain according to their reliability [54], e.g., the more reliable a sense is, the higher weight it will get [21, 22, 36]. This sensorimotor information is interpreted by the brain based on daily life experience to conclude final perceptive results [53, 73]. This means that locomotion methods with natural sensory stimulation similar to daily locomotion experience are conducive to improving VR locomotion performances. Moreover, a physiological mechanism of the vestibular system causes decreased motion sickness [32] and increased self-orientation deviation of users at reclining & lying positions [99]: the bigger the angle between the vestibular system and the gravitational direction is, the lower the vestibular sensitivity and weight in the sensory integration process [1, 58, 94]. Specially, when the vestibular sense perceives no acceleration, the brain usually relies on other senses to distinguish whether the body is in static or uniform motion [48].

Recently, a lot of VR studies use redirected views to achieve certain locomotion-related functions by visually decoupling the mapping between virtual and real worlds [76, 100], such as walking redirection [20, 75], jumping redirection[98], and teleportation redirection [28], etc. However, these visual manipulations cause extra sensory conflict in VR, thus affecting spatial perception [23], self-motion sensation [66], illusions [70] and motion sickness [72].

Sensory integration theory provides a theoretical basis for explaining the effects of VR redirection on users. Based on this, several studies explored the sensory conflict problems of upright redirection in the users' non-motion state or locomotion by joystick [38, 39, 58]. A recent research [92] took a qualitative approach to investigate the user experiences and identify benefits as well as interaction challenges in lying down users. From their results, it can be seen that navigation is expected but is a significant limitation. However, these studies did not provide or evaluate potential interaction techniques or designs. Compared with these studies, our work is different in two ways: 1) our topic is more specific, with a focus on the navigation problem; 2) we pay special attention to the effect of various physical constraints and sensory conflict levels caused by the body leaning angles on the locomotion methods.

The solutions for reducing sensorimotor conflicts include enhancing multi-sensory matching [90], suppressing conflicting sensory signals [13], and using metaphors that fit with daily sports experience in locomotion methods [46]. It is essential to understand the importance of sensory stimuli and metaphors of locomotion methods in the framework of sensorimotor theory, especially the sensory conflict cases. This knowledge helps providing the theoretical basis for interpreting the redirection effects in Study 2. The methods of reducing sensory conflict inspire novel strategies for improving the locomotion methods in Study 3.

3 STUDY 1: USER-ELICITED LOCOMOTION METHODS

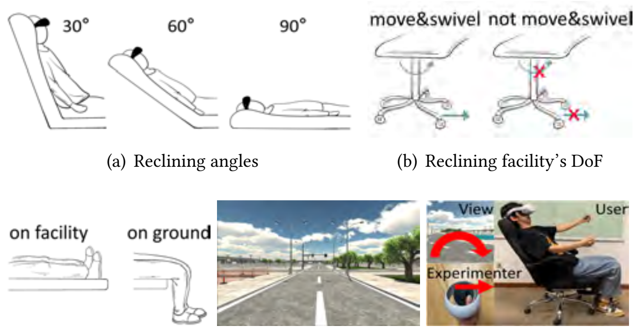
This study aims to elicit reclining & lying users with upright redirected views to design ground-based locomotion methods, and explore users' preferences and the impact of different reclining & lying conditions on the design spaces.

3.1 Ethics, Participants, Conditions, and Devices

The experiment obtained ethics approval from a local university. For participants' safety and comfort, we did not recruit people with vestibular disorders or who experienced severe motion sickness symptoms. After recruitment, participants were required to try a VR racing game "Mini Motor Racing X" [64] for 15 minutes for further screening. If no severe motion sickness symptoms appeared according to participants' feedback and our observation, they could sign the informed consent form and schedule their formal experiment time (on another day) with us.

We recruited 24 students (10 female, mean age=23.25 (SD=2.13), age range: 19-28) from a local university. The number of participants with VR experience of proficiency (often use VR apps), some proficiency (not often use VR apps), and none were 6, 10, and 8 respectively. To adapt to the commonly used reclining facility (e.g., chairs, sofas, beds, etc.) in daily scenarios, we designed 3*2*2=12 conditions: 30°, 60° and 90° reclining angles (Figure 2(a)), move & swivel and not move & swivel according to the reclining facility's DoF (Figure 2(b)), feet on ground and on facility according to the feet positions (Figure 2(c)). Noticeably, feet on facility implied that the participants cannot move and swivel the facility, so 3 conditions were removed and a total of 9 conditions left (i.e., C1-C9 in the last row of Tables 1 and 2). There are two reasons for not separating the reclining facility's moveable and swivelable abilities: First, separating movable and swivelable abilities may result in too long experiment time, which may affect the enthusiasm of the participants. Secondly, this design is to provide more DoF to stimulate the participants' imagination, e.g., moving the chair to map the view's rotation or rotating the chair to map the view's movement.

We used an Oculus Quest 2 [83] as the VR headset. A swivel chair with an adjustable backrest angle was used to simulate all conditions. To simulate the feet on facility (e.g., sofas, beds), we used another chair of similar size for the participants to put their legs/feet on. It was worth mentioning that in the application scenarios (chair, sofa, bed, etc.) simulated by each condition, we told the participants to avoid the gestures being limited to the chair.



(a) Reclining angles (b) Reclining facility's DoF

(c) Feet positions (d) Experimental scene (e) Wizard-of-Oz

Figure 2: Conditions, scene, and procedure in Study 1

3.2 Interface Design

The virtual scene was composed of town streets with plenty of upright reference objects, as shown in Figure 2(d). When the participants were reclining or lying comfortably in the target positions and looking forward, a calibration procedure of redirecting the tilted virtual view to be parallel to the ground was performed. Like previous user-elicitation studies, we did not render avatars [4], and the participants could freely imagine themselves walking, driving, etc. during locomotion.

3.3 Procedure

For each condition, we first controlled the participants' views to move (i.e., going forward and backward) and turn (i.e., turning left and right) by the controller, and took these two locomotion trajectories as referents. We then asked the participants to design two gestures for each referent using strict think-aloud protocols [26] in each condition. In this process, the participants were asked to explain the gestures and describe the gestures' control methods (i.e., how to start, continue, stop, and map the speed) and the design motivations (i.e., inspiration and advantages). The design principle to follow was their own feeling of being suitable, natural, intuitive, and comfortable in the conditions. The gestures designed for different conditions could be repetitive.

Next, the participants were asked to demonstrate the gestures, and an experimenter adjusted the controller to cooperate with the views with their actions accordingly, as shown in Figure 2(e). During the process, we asked the participants to describe their intuitive feelings, such as self-motion sensation, fatigue, acceptability, etc. Then, the participants were required to reflect on their favorite moving and turning gestures for each condition. At the end of the study, the participants were interviewed and asked to choose their favorite gestures, reclining angle, foot position, and the reclining facility's DoF among all the conditions.

This study used a repeated-measures design. It took about 1.5 hours for each participant to complete the experiment (including rest and interview). Each participant got about 20$ cash for rewards.

3.4 Measurements of Mitigating Bias

The experiment had 2 experimenters. One was responsible for instructing the participants and recording their gestures, feelings, and preferences, etc. by text and simple diagram, and the other was responsible for controlling referents and the Wizard-of-Oz. The experimenters were trained to mitigate the experiment bias, including proficiency instruction and accurate recording, and proficiency controller manipulation to match the participants' gestures in Wizard-of-Oz as fast and accurately as possible. Through the official casting function of Oculus [85], a computer real-time displayed the participants' view for experimenters.

To eliminate the latent effect and learning effect of repeated measures, the order for each participant to experience conditions was randomized with counterbalance. That was, each participant randomly drew an order without repetition among all possible combinations of all conditional orders, given that the possible orders (9!) were far greater than the users (24). Between conditions, we asked the participants to rest until they had no subjective discomfort and fatigue feelings (if any) for eliminating the carry-over effect. We constantly asked them to confirm verbally that they had returned to their pre-experimental feelings. Otherwise, the next task would not be started. In this experiment, no one quit the experiment.

3.5 Evaluation Methods

The counts of appearances and preferences for a designed gesture reflected its intuitiveness and practicality, respectively. We first classified user-elicited moving and turning gestures, and calculated the counts of appearances and preferences for each type of gesture under various conditions.

The classification method was that three of the authors discussed and determined the main features of the gestures (subject and controlled method) according to the gestures' actions and the participants' descriptions, and the gestures with the same main features were classified as the same gesture. For example, the subject of the gesture 'calf tilting' (Figure 3(a)) was the calf, and the controlled method was to map the view's turning speed by the calf's leaning amplitude. Although calf tilt caused a certain chair's rotation in some conditions, it was classified into 'calf tilting' rather than 'chair rotating' (the chair's turning speed mapped the view's turning speed) due to the different main features.

We further categorized all the gestures into dynamic (i.e., action kept moving or rotating in real-time), semi-dynamic (i.e., action needed to move or rotate when changing the locomotion speed), and static (i.e., action kept static during the whole virtual locomotion) gestures, to analyze user preferences of control methods. For example, 'foot friction' (Figure 3(c)) and 'hand push-pull' (Figure 3(d)) were dynamic gestures, because the participants needed to repeat the friction or push-pull action to maintain view's move, and used the action's speed to map the view's moving speed. 'Calf tilting' (Figure 3(a)) was a semi-dynamic gesture, because when the participants' calves tilt left/right, their view will continue to turn left/right, and they only need to change the calves' leaning amplitude when the view's moving speed needs to be changed. 'Cross-legged' (Figure 3(b)) was a static gesture. As the participants found it difficult to further move their legs to map the view's moving speed in cross-legged state, the gesture's speed mapping method was usually not designed (i.e., fixed speed).

To assess the agreement degree among gestures elicited from various participants, we calculated each conditional agreement rate separately. The agreement rate AR for each referent t was calculated using Equation (1) [93]:

$$AR_{(t)} = \sum_{M_i \subseteq M} \frac{M_i(M_i - 1)}{M(M-1)}, \quad (1)$$

where M represented the total number of elicited gestures for a referent, and M_i represented the number of a subset i of identical gestures from M. Qualitative interpretations for agreement rate were as follows [93]: *low* ($AR \leq 0.1$), *moderate* ($0.1 < AR \leq 0.3$), *high* ($0.3 < AR \leq 0.5$), and *very high* ($AR > 0.5$). The agreement rate was derived using a gesture set that only considered one gesture per participant. So we used the per participant's preferred gesture to calculate AR for each condition. Finally, we counted overall preferences of gestures and conditions.

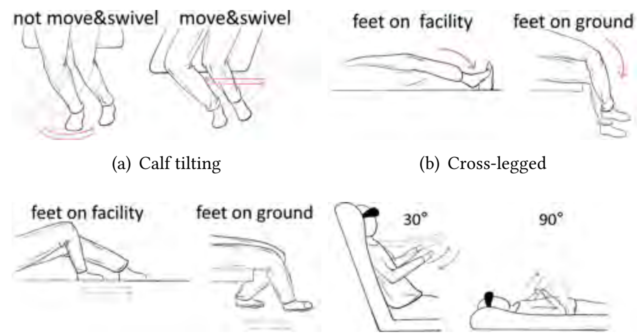
3.6 Experimental Results

3.6.1 User-elicited Locomotion Methods. We collected 24*9*2=432 moving gestures and turning gestures, respectively. After classification, there were 51 different moving gestures (i.e., 17 via leg/foot, 27 via arm/hand, 2 via torso, 4 via head, and 1 via hip), and 50 different turning gestures (i.e., 14 via leg/foot, 30 via arm/hand, 2 via torso, 3 via head, and 1 via hip). The leg/foot gestures had the highest appearance count (i.e., moving 257, turning 221) and preference count (i.e., moving 137, turning 127).

Dynamic gestures were the most (i.e., 32 moving gestures, 24 turning gestures), followed by semi-dynamic gestures (i.e., 16 moving gestures, 24 turning gestures), and static gestures were the least (i.e., 3 moving gestures, 2 turning gestures). The design of ending gestures includes those for stopping continuous actions, often affiliated with dynamic gestures, and returning to pre-action states, often affiliated with semi-dynamic and static gestures. For the design of speed mapping, the action's amplitude was commonly used in semi-dynamic gestures, and the action's speed and frequency were commonly used in dynamic gestures.

The top 10 moving and turning gestures were presented in Tables 1 and 2, respectively. The data before semicolons represented the appearance count, and the data after semicolons represented the preference count of gestures. The agreement rates of each condition were shown in brackets in the first row, where black, blue, magenta, and red represented *low*, *moderate*, *high*, and *very high* agreement rates, respectively.

3.6.2 Overall Preferences. The number of preferences was sorted in descending order: tapping (11), leg joystick (3), backstroking (3), knee tapping (2), foot friction (2), hand push-pull (1), accelerator pedal (1) and finger pointing (1) for moving gestures; chair rotating (18), calf tilting (2), torso rolling (1), foot pointing (1), knee pointing (1), and cross-legged (1) for turning gestures. In terms of reclining angles, 7 participants preferred 30°, 4 participants preferred 60°, and 13 participants preferred 90°. For foot positions, 17 participants preferred feet on ground and 7 participants preferred feet on facility. For the reclining facility's DoF, 22 participants preferred move & swivel, and 2 preferred not move & swivel.



(a) Calf tilting (b) Cross-legged

(c) Foot friction (d) Hand push-pull

Figure 3: Same method's various forms in various conditions

3.6.3 Comparison of Different Conditions. As shown in Table 1, for moving gestures, Conditions 1 to 4 and 7 had *low* agreement rates, and Conditions 5,6,8, and 9 had *medium* agreement rates. As shown in Table 2, for turning gestures, Conditions 1, 2, and 5 had *low* agreement rates, Conditions 4, 7, and 8 had *medium* agreement rates, Condition 6 had *high* agreement rate, and Conditions 3 and 9 had *very high* agreement rates. The appearance counts of the torso, head, arm/hand related gestures were the highest under 30° condition (75 of moving gestures, 85 of turning gestures), and on the contrary, were the least under 90° condition (46 of moving gestures, 56 of turning gestures). For leg/foot-related gestures, their appearance count was the highest in feet on ground-move/swivel condition, whilst the least in feet on facility-not move/swivel condition. Noticeably, the same locomotion methods had distinctive forms and features under different conditions (Figure 3).

3.7 Discussion

Overall, various conditions had different design features and preferences due to the effects of interacting postures and view redirection.

First, it was found that physical constraints under different conditions affected the gesture designs. The feet-on-facility condition limited the leg/foot action, resulting in the least leg/foot gestures. Yet we found that many users in this condition elicited similar foot gestures as feet-on-ground condition, when their knees were bending (Figure 3(c)). In the 30° condition, the participants could easily perform various actions with different body parts, leading to more diverse gestures but with low agreement rates. For the 60° and 90° conditions, the torso, head, and arms needed to exert more effort when acting, the gestures of which were thus fewer. In arm/hand gestures of 90° condition, most participants tended to place the rear arm on the chair and used only the forearm or hand to perform actions to reduce the gorilla arm effect (Figure 3(d)).

Second, upright redirection interfered users' original consistency in multi-sensory perception of body orientation, resulting in extra

Table 1: User-elicited Moving Gestures and Their Counts of Appearances & Preferences (Top 10 Sorted by Appearance Count)

Gestures (*AR*)	C1 (0.062)	C2 (0.058)	C3 (0.069)	C4 (0.098)	C5 (0.101)	C6 (0.138)	C7 (0.072)	C8 (0.101)	C9 (0.127)	Total
foot tapping	5;3	7;5	9;5	7;4	11;6	14;8	8;5	11;6	13;8	85;50
finger pointing	8;4	6;2	6;3	6;5	4;2	5;1	4;3	4;2	5;3	48;25
accelerator pedal	3;2	4;2	7;1	5;4	6;4	5;4	6;2	6;4	3;2	45;25
leg joystick	1;1	3;1	3;2	1;1	3;2	4;3	4;2	5;2	7;3	31;17
backstroking	4;2	3;2	4;2	5;3	2;1	2;2	2;2	3;0	1;1	26;15
walking-in-place	2;1	4;1	3;2	0;0	5;1	4;0	1;0	2;1	4;1	25;7
knee tapping	5;3	2;1	1;0	5;1	2;2	1;1	4;3	2;2	1;1	23;14
foot friction	1;0	3;2	3;2	0;0	2;1	1;1	2;0	3;2	3;1	18;9
hand push-pull	2;1	2;2	2;1	4;1	3;1	0;0	3;1	1;0	0;0	17;7
chair moving	0;0	0;0	4;2	0;0	0;0	6;3	0;0	0;0	5;1	15;6

C1: 30-F-N| C2: 30-G-N| C3: 30-G-Y| C4: 60-F-N| C5: 60-G-N| C6: 60-G-Y| C7: 90-F-N| C8: 90-G-N| C9: 90-G-Y
30,60,90: various reclining angle| F: feet on facility| G: feet on ground| N: not move&swivel| Y: move&swivel

Table 2: User-elicited Turning Gestures and Their Counts of Appearances & Preferences (Top 10 Sorted by Appearance Count)

Gestures (*AR*)	C1 (0.047)	C2 (0.036)	C3 (0.764)	C4 (0.105)	C5 (0.036)	C6 (0.391)	C7 (0.112)	C8 (0.138)	C9 (0.630)	Total
chair rotating	0;0	0;0	24;21	0;0	0;0	20;15	0;0	0;0	23;19	67;55
foot pointing	7;4	6;3	3;0	8;7	5;4	3;1	8;5	10;3	7;0	57;28
finger pointing	5;1	4;3	2;0	4;3	5;1	3;0	5;1	5;2	3;0	36;11
torso rolling	4;2	1;0	2;0	5;2	4;2	1;0	5;4	3;2	3;1	28;13
cross-legged	3;2	3;1	1;0	2;2	3;2	1;1	6;4	6;1	2;0	27;13
calf tilting	2;0	5;2	3;2	0;0	3;0	3;3	0;0	2;2	4;3	22;12
knee pointing	1;1	2;0	1;0	3;1	3;2	4;0	2;2	3;3	1;0	20;9
steering wheel	3;3	5;2	4;1	3;0	2;0	0;0	1;0	0;0	0;0	18;6
take a step	2;1	2;1	0;0	1;0	2;1	1;1	4;2	3;0	1;0	16;6
hand swiping	3;1	3;1	1;0	3;1	1;1	1;1	2;2	1;1	0;0	15;8

C1: 30-F-N| C2: 30-G-N| C3: 30-G-Y| C4: 60-F-N| C5: 60-G-N| C6: 60-G-Y| C7: 90-F-N| C8: 90-G-N| C9: 90-G-Y
30,60,90: various reclining angle| F: feet on facility| G: feet on ground| N: not move&swivel| Y: move&swivel

sensorimotor conflicts that influenced the gesture design. Most participants (23 people, 95.8%) suggested they could accept these settings of upright redirected locomotion. However, many participants (18 people, 75%) reported that they had various levels of upright locomotion feelings, while they still felt their body leaning backward, which was incongruent and negative to their immersion. They described their locomotion feelings as strange, confused, and sometimes dizzy. Interestingly, although the participants were in their comfortable reclining & lying positions, they did not tend to design relatively effortless gestures. Rather, they preferred semi-dynamic or dynamic gestures with locomotion metaphors to match their upright locomotion views. This suggested gestures that provided strong vestibular or proprioceptive stimuli, especially with motion metaphors in daily life, were beneficial to natural locomotion feelings and good immersion in upright redirection.

According to the participants' experience in Wizard-of-Oz, the natural self-motion sensation was one of the key factors for the participants to like the gesture. Dynamic gestures with daily locomotion metaphors were generally thought to enable them to be more adaptive upright locomotion while ignoring physical body posture to a certain extent. Typical metaphors included walking (e.g., foot tapping, walking-in-place), driving (e.g., accelerator pedal, steering wheel), swimming (e.g., backstroking), skiing (e.g., calf tilting), etc. In contrast, the participants thought the self-motion sensation and immersion of some static and semi-dynamic gestures without locomotion metaphors were less, and the motion sickness was stronger, although the gestures were effort-saving, e.g., finger/foot pointing, leg joystick, cross-legged, etc. Considering most participants' experiences, preferences, and the redirection effects, it can be seen that maintaining the users' self-motion sensation and immersion under the sensorimotor conflict was the primary priority. As a result, we recommended using top-ranked gestures with locomotion metaphors and strong sensory stimulation for reclining & lying VR users.

'Tapping' and 'chair rotating' had the most counts of appearances and preferences among all the gestures. 'Tapping' provided the participants with a good balance of natural self-motion sensation and effort-saving compared to 'walking-in-place' and 'finger pointing', and could be applied to all the conditions. 'Chair rotating' shared the same benefits because it had the most natural vestibular-proprioception stimulation. Moreover, 'tapping' represented a class of strong proprioceptive stimulation methods with moving metaphors, which included backstroking, walking-in-place, knee tapping, foot friction, etc. 'Chair rotating' represented a class of vestibular & proprioceptive stimulation methods with turning metaphors, such as torso rolling, head left/right-leaning, torso left/right-leaning, etc. Therefore, they could be used as representatives in further studies for measuring the general effects of posture and upright redirection.

Moreover, half of the participants (12 people, 50 %) reported that they felt more upright under the 90° condition, which was the largest redirected angle we experimented with. Some participants (10 people, 42 %) described "an easier experience" in performing leg-related gestures, e.g., actions of 'chair rotating', 'walking-in-place', 'cross-legged' etc., at 90° condition than other conditions. These results indicated that participants' locomotion general performances related to their body's reclining angle, which required further explorations.

4 STUDY 2: PERFORMANCES OF 'TAPPING' AND 'CHAIR ROTATING'

As a first exploration, there were a rich set of conditions and elicited locomotion methods in Study 1. This study aims to investigate the performances of representative locomotion methods, and measure the general impacts of posture and redirection. We believe that body angle is the most closely related to the reclining postures' features and redirected sensory conflict among all conditions. So we select to investigate the performances of 'tapping' and 'chair rotating' at feet on ground-move/swivel (i.e., users' favorite condition) with different reclining angles conditions.

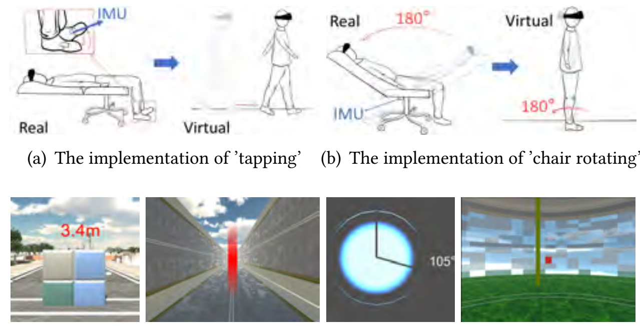
4.1 Implementation

According to Study 1, 'tapping' forward was designed as the forefeet tapped on the plane alternately while keeping the heels on the plane, and 'tapping' backward was the opposite: the heels tapped on the plane alternately while keeping the forefeet on the plane. To track the actions of the feet, we fastened two IMUs (Wit-motion Wireless IMUs (type: BWT61CL) [84]) to users' shoes with straps.

We designed an algorithm to identify the beginning, continuation, and stop of 'tapping' by angle and time. The method of speed mapping adopted the design from Study 1, which mapped the feet's angular speed to the moving speed of views, as shown in Figure 4(a). For 'chair rotating', the physical turning process was approximate to the user's HMD revolving around the center axis of the chair (multi-axis revolution with arc-shaped displacement), and the corresponding virtual view in VR was a self-centered turning (single-axis yaw turning without displacement). We used an IMU to track the chair's swiveling to distinguish head-turnings and chair-turnings. We mapped the multi-axis revolution of the HMD to the self-centered turning of virtual views, as shown in Figure 4(b).

4.2 Experiment Tasks and Interface Design

Users' estimations of locomotion distance and angle were important for the formation of accurate space awareness (i.e., path integration and self-location by processing sensorimotor cues), without which it was easy to get lost in VR. Such estimations were often used as



(a) The implementation of 'tapping' (b) The implementation of 'chair rotating'

(c) Input distance (d) Moving to target (e) Input angle (f) Turning to target

Figure 4: Implementation and experimental tasks

tasks in studies involving sensory conflict [6, 15, 40, 71]. Moreover, the ability of users to reach targets accurately was seen as an important metric when evaluating the accuracy & controllability of locomotion methods [30, 31]. Inspired by these, we designed two tasks for the two locomotion methods, respectively.

This experiment contained 3 virtual scenes whose size proportions were consistent with the real world: practice scene, moving task scene, and turning task scene. The practice scene was town roads with signs of distances or angles for the participants to practice the two locomotion methods. The moving task scene was an infinite road with upright walls on two sides. The turning task scene was an indoor lawn in a cylindrical building. The two task scenes' textures were randomly generated for preventing counting strategies based on visual referents [40] during the locomotion process. Each task was repeated 6 times, 3 times each for moving forwards and backwards, or 3 times each for turning left and right.

Task 1 - Distance Perception in Moving: This task was modified from Campos' study [15]. The participants were first asked to use 'tapping' to move forwards or backwards in the moving task scene for a predetermined distance (random between 3m to 10m) which was unknown to the participants. Then, the participants were teleported to the practice scene, and asked to estimate the distance they walked by adjusting the ego-to-target distance of a target object there, as shown in Figure 4(c). Once the participants were satisfied with the target position, they pressed a button to confirm. The purpose of these designs was to prevent participants from estimating the distance through visual inspection in advance, and to reduce the visual memory retention of the task scene.

Task 2 - Accuracy & Controllability in Moving: This task was modified from Gao' study [30]. In the moving task scene, a random translucent red cylindrical target (radius was random between 0.2m to 0.5m) was placed at a random distance of 3-30m in front of or behind the participants' current position [31]. When the participants were 2m away from the target, a prompt text appeared to indicate the participants to stop. The participants needed to control the view to stop in the target area and press the button to confirm, as shown in Figure 4(d). If succeeded, a next random target would appear.

Task 3 - Angle Perception in Turning: This task's design was similar to Task 1's. The participants were first asked to virtually turn left or right in the turning task scene until they reached a predetermined

Table 3: Five Single-item Scales

Scales	Question	Scores & Labels
Upright Motion Sense	How much do you feel you are in upright locomotion now?	0: not at all
Presence	How much do you feel you really exist in this virtual world now?	1: not so much
Ease of Control	How easily do you feel you can control the locomotion method now?	2: so-so 3: a little
Fatigue	How tired do you feel now?	4: quite a lot
Motion Sickness	How much do you feel your symptoms of motion sickness now?	5: very much

angle (random between 20° to 180°) which was unknown to them. Meanwhile, the locomotion was forced to abort and a disc appeared on grey background. As shown in Figure 4(e), the disc had an hour hand fixed at 12 o'clock and a minute hand. The participants needed to adjust the minute hand to the left or right until the angle between it and the hour hand was the same as the view-turned angle.

Task 4 - Accuracy & Controllability in Turning: This task was similar to Task 2's. In the turning task scene, a red cube was generated 7.5m in the chair's facing direction and rotated with the chair. A green cylindrical target was placed at the 7.5m distance from the view's current position and the angle between it and the view's facing was random. If the target was in the view, it could cover a certain view angle (random between 5° to 15°). The participants needed to control the red cube to stop in the target area and pressed the button to confirm, as shown in Figure 4(f).

4.3 Participants, Conditions, and Devices

We recruited a new group of 20 students as participants (8 female, mean age=22.5 (SD=1.91), age range: 18-27) from a local university. The number of participants with VR experience of proficiency, some proficiency, and no were 5, 8, and 7 respectively. For the reclining angle, we divided the angle (i.e., 0° to 90° relative to the gravity direction) into 5 equal angular divisions, resulting in: 0°, 22.5°, 45°, 67.5°, and 90° reclining & lying conditions. Among them, the 0° sitting position without upright redirection was used as a control condition to measure the potential effects of posture and sensory conflict on locomotion methods' performances. The other setup was the same as Study 1's.

4.4 Procedure and Measurements

This study used a repeated measures design. First, we asked the participants to get familiar with the two locomotion methods and the spatial relationship during locomotion in the practice scene. Among them, the participants needed to choose a position where their feet were comfortable to go forward and backward during 'tapping', and put their feet in this position during subsequent moving tasks. Then, the participants were transported to the formal experimental scene and asked to complete the 4 tasks in random order as accurately as possible. After completing each condition, the participants were interviewed for their subjective feedback.

The measurements of ethics & safety, mitigating repeated measures' effects were the same as Study 1's. No one quit in this experiment. Each participant took about 2 hours for the experiment (including rest and interview) and got about 30$ cash for rewards.

4.5 Evaluation Methods

For perception tasks of distance and angle, we used the deviation percentage (i.e., the ratio of the difference between perceptive distance/angle and actual distance/angle to actual distance/angle) as the perceptive metrics. For the two accuracy & controllability tasks, we used the overshoot number as a functional metric, which was defined as the number of times that the participants entered the target area and then left it without confirming, following the same approach of previous work that measured the controllability and accuracy of the locomotion method [30, 52, 101].

The evaluation method of subjective metrics was modified from Thorp's study [87]. For each condition, the participants were asked to fill out 5 single-item scales to evaluate 5 metrics (Table 3) after each task was repeated twice (i.e., 6 times of moving tasks and turning tasks respectively), where the 6 times' median value served as each metric score. Questions and options were displayed in VR and chosen by participants. Such fast single-item scale had been widely used in the evaluation of motion sickness [42], presence [10], etc. These studies suggested that this method could capture the moment's experience more accurately and also was less sensitive to memory deterioration compared to multi-item scales [87, 91], and had high correlations with the typical scales, such as SSQ [41], etc. With a few pilot tests, we found that most participants needed to spend relatively long time for repeatedly weighing between several adjacent scores when scoring. Considering that our scales were more than Thorp's study, numerous options might cause bias due to cognitive load, we narrowed the score range from 1-10 to 0-5.

4.6 Experiment Results

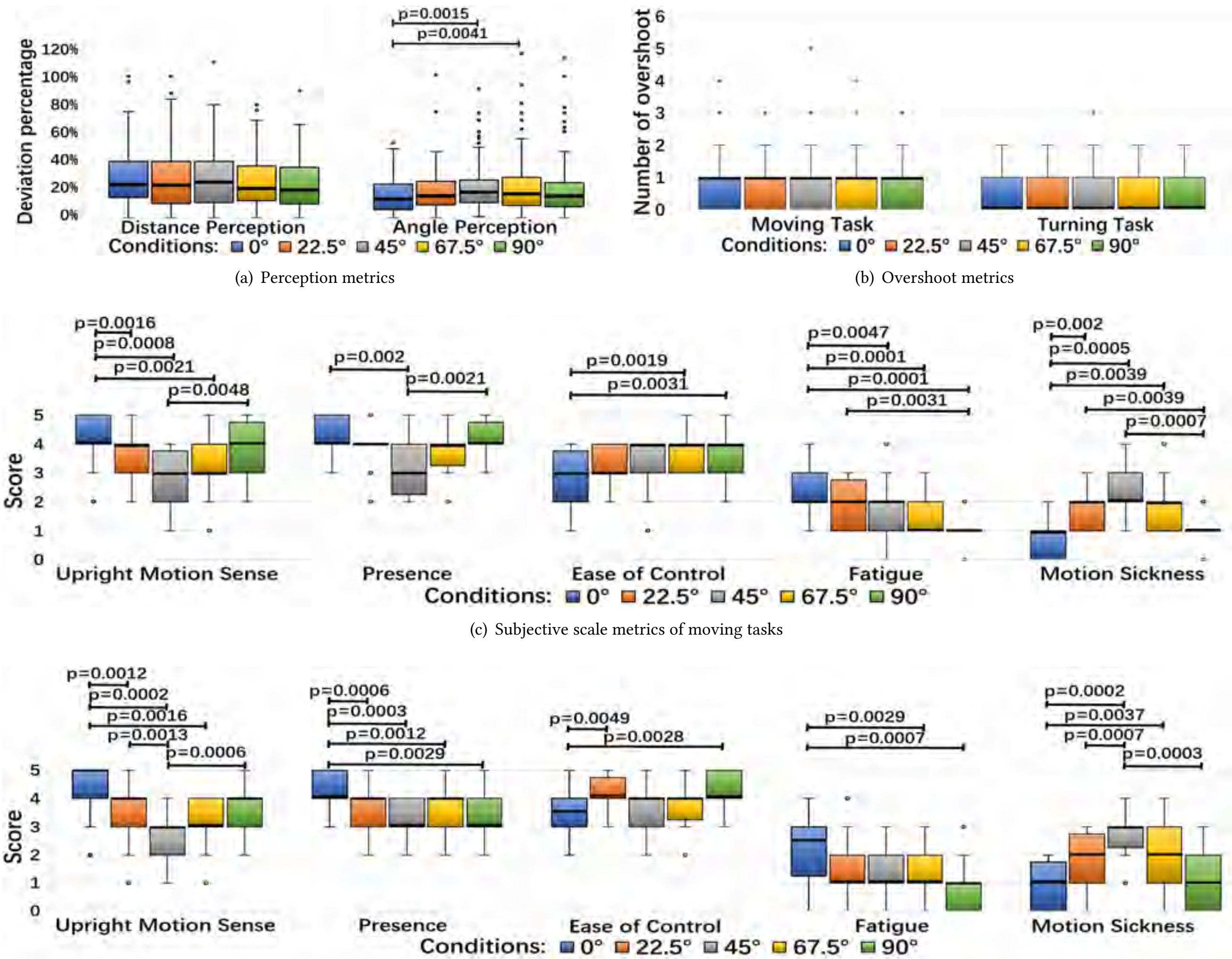
According to Shapiro-Wilks tests, some conditions' metric data were not normally distributed. Therefore, we used Friedman ANOVAs with pairwise Wilcoxon signed rank tests with Bonferroni correction for post hoc comparisons between conditions, resulting in a new significance level set at $p < 0.005$ in post hoc comparisons.

4.6.1 *Perceptive & Overshoot Metrics.*

The results showed the reclining angle had a significant effect on angle perception ($\chi^2(4) = 12.230$, $p = 0.016$), but had no significant effects on distance perception or overshoot number, as shown in the boxplots in Figure 5(a) and (b). Horizontal lines with p-values between conditions represented exist significant differences in post hoc comparisons. Overall, 0° Condition performed best in spatial perception.

4.6.2 *Subjective Scales.*

In the trials where the participants used 'tapping' to move, the ratings of Upright Motion Sense($\chi^2(4) = 28.607$, $p < 0.001$), Presence($\chi^2(4) = 22.068$, $p < 0.001$), Ease of Control($\chi^2(4) = 16.315$, $p = 0.003$), fatigue($\chi^2(4) = 35.574$, $p <$



(a) Perception metrics

(b) Overshoot metrics

(c) Subjective scale metrics of moving tasks

(d) Subjective scale metrics of turning tasks

Figure 5: The results of the performances of 'tapping' and 'chair rotating'

0.001), and motion sickness($\chi^2(4) = 38.841$, $p < 0.001$) differed significantly between the different recline angle conditions. In the trials where participants used 'chair rotating' to turn, ratings of Upright Motion Sense($\chi^2(4) = 50.611$, $p < 0.001$), Presence($\chi^2(4) = 30.016$, $p < 0.001$), Ease of Control($\chi^2(4) = 23.084$, $p < 0.001$), fatigue($\chi^2(4) = 26.076$, $p < 0.001$), and motion sickness($\chi^2(4) = 41.037$, $p < 0.001$) differed significantly between the different recline angle conditions. The boxplots of the metrics data and significant differences with p-values of post hoc comparisons were shown in Figure 5(c) and (d). Overall, in natural upright motion sense, strong presence and low motion sickness, 0° Condition and 45° Condition usually performed the best and the worst respectively. In ease of control and low fatigue, 90° Condition and 0° Condition usually performed the best and the worst respectively.

4.7 Discussion

Overall, the participants' feedback on the two locomotion methods was positive. Most participants (18 people, 90%) thought the two methods were effective in the locomotion tasks. Moreover, it was found that the performances of the two locomotion methods could be significantly affected by the body angle & redirection angle.

4.7.1 The Effect of Upright Redirection on Perceptive & Experiential Metrics. Overall, due to sensorimotor conflicts, upright redirection affected users' angle perception, upright motion feeling, presence, and motion sickness. Specifically, during 'tapping', vision and proprioception perceived forward/backward motion with variable speed, but the vestibular sense perceived no motion or tilting upward/downward motion with uniform speed due to that vestibular sense could perceive body orientation and acceleration but cannot distinguish between static and uniform motion [7]. During 'chair rotating', vision perceived yaw rotation without displacement, but vestibular sense and proprioception perceived different direction revolutions with arc-shaped displacement trajectories.

Interestingly, 45° Condition was generally the worst, and 90° Condition had the biggest redirected angle yet performed the best on most metrics in all reclined conditions. According to the knowledge of sensorimotor integration and the fact that body-gravity angle affects vestibular sensitivity (See Section 2.2), we speculated that the U-shape between conditions was attributed to the combined effect of two aspects. On the one hand, as the body reclining angle increased, the redirection angle should cause a bigger sensorimotor conflict according to other redirection techniques, and this should make the sensory conflicts from 0 to 90 degrees increase sequentially. On the other hand, the increased body reclining angle inhibited the vestibular sensitivity and decreased its sensory integration weight [1, 94, 99], and reduced upper-lower body's bending that made the proprioception felt more 'upright', thereby reducing sensorimotor conflict impacts. The combined effects of these two aspects made the influence of sensory conflict first increase and then decrease with the increase of body reclining angle, and reached the maximum at 45°.

The effects & causes discussed in this section were generally due to many other locomotion methods having the same sensorimotor conflict types as these two methods. For instance, walking-in-place, knee tapping, and foot friction also had multi-sensory moving direction & acceleration conflicts. Similarly, turning methods like torso rolling, and head/torso left/right-leaning also had multi-sensory rotation axes/directions & motion trajectories conflicts. Therefore, we believed that such difference results between conditions could be generalized to more conditions and the locomotion methods with the same types of sensory stimuli & conflicting.

4.7.2 The Effect of Posture on Functional Metrics. Overall, the body reclining angle was found to affect the controllability and fatigue of the locomotion methods. We found that the bigger the reclining angle was, the participants felt less fatigue and easier body control. On the other hand, many participants (11 people, 55%) reported that they were more tired to perform heels 'tapping' and 'chair rotating' at 0° Condition. We speculated that the entire upper body weight supported on the waist and hips in the sitting position resulted in a certain resistance to the thigh movements. With the reclining angle increased, the pressure and resistance decreased, which made the legs easier to perform actions such as lifting the thighs during heels' 'tapping', and separating the thighs during 'chair rotating'. We believed the posture's effects could be generalized to more leg/foot gestures and conditions.

4.7.3 Other Findings. We found that most participants (19 people, 95%) chose to place their feet in a position where the calves and insteps presented about 90°. It indicated that this position was a balanced position for controlling forward and backward movements, which was because bigger angles between the calves and insteps made it easier for the forefeet to lift higher, but harder for the heels to lift. It worked oppositely with smaller angles.

Most participants (15 people, 75%) liked to tap their feet regularly and keep at a fixed speed, because they thought it would be more relaxed, easy to perceive distance, and less dizziness. For some moving tasks with long distances (e.g., accuracy & controllability task), half of the participants (11 people, 55%) tended to fast 'tapping', and then suddenly decelerated when approaching the target. However, this produced the most overshoots. For 'chair rotating', the angle's overestimation to underestimation ratio for the 0° Condition was about 1:1 (62:58). However, the participants in 4 reclining & lying positions tended to overestimate (347:133) and they felt the physical body turned more than their views. We speculated that this was due to the vestibular sense perceiving arc-displacement of revolution.

5 STUDY 3: DESIGNING IMPROVED METHODS OF 'TAPPING' AND 'CHAIR ROTATING'

Although 'tapping' and 'chair rotating' were found to be effective, these two methods had some disadvantages, e.g., the insufficient upright motion sense, motion sickness, fatigue, and overshoot caused by real-time speed control of 'tapping', angle's overestimation and motion sickness caused by revolution arc-displacement of 'chair rotating', etc. This study aims to upgrade the two methods to further strengthen the two locomotion methods.

5.1 Improved Method Design

We proposed 4 upgraded methods for 'tapping' and 'chair rotating'.

'Tapping' with grading & uniform speed: Based on the vestibular system could only perceive acceleration and could not distinguish between statics and uniform motion [7], we set the 'tapping' to fixed speeds. In addition to normal walking speed, paired fast and slow uniform speeds are also necessary to save time and prevent easy overshooting in fast speed respectively. We divided tapping into three forms: when the calves-insteps angles were within 75°, it was easier to raise the heel and tap which could bring large vibrations like running, so the heel tapping was set to run forwards at 3.5m/s [27]. Correspondingly, using the resistance of the forefoot was not easy to raise at this position, the forefoot tapping was set to slow walk forwards at 0.5m/s [81], as shown in Figure 6(a). When the calves-insteps were at other angles, the tapping function was the same as in Study 2, but the speed is fixed at 1.2m/s [65]. As people seldom step back with fast speed in daily life, we did not set the fast speed and corresponding slow speed for going backwards.

'Tapping' with head shaking: Left/right shaking head [86] showed an enhanced motion experience due to its similarity with the walking experience that the view sways with the step of the left and right legs. We utilized the fact that head shaking in the reclining & lying positions was easy, and asked the participants to actively cooperate with the 'tapping' action to shake their heads, as shown in Figure 6(b).

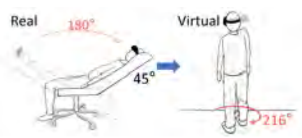
'Chair rotating' with arc-trajectory: During the turning process, we directly mapped the HMD's revolution displacement (arc-shaped trajectory) to the upright view, so that the upright view changed from self-centered turning to revolve around the chair's center axis for reducing the sensory conflicts, as shown in Figure 6(c).

'Chair rotating' with turning gain: We mapped the revolution displacement to the extra turning gain of view. The turning gain for each condition was set to the median of the perceived deviations ratio from all overestimated data in Study 2: 0.13 in 22.5° Condition, 0.20 in 45° Condition, 0.16 in 67.5° Condition, 0.15 in 90° Condition, as shown in Figure 6(d).

(a) 'tapping' with grading & uniform speed

(b) 'tapping' with head shaking

(c) 'chair rotating' with arc-trajectory



(d) 'chair rotating' with turning gain

Figure 6: Upgraded methods of 'tapping' and 'chair rotating'

5.2 Participants, Conditions, Scenes and Devices

We recruited a different group of 20 students as participants (13 male and 7 female, avg. age=22.2 (SD=1.68), age range: 19-26) to validate the proposed methods. The number of participants with proficiency, some proficiency, and no VR experience was 4, 10, and 6 respectively. We chose the condition of 45 ° reclining position as the experimental posture, the one with the worst performance but the most worthy of improvement. Six conditions were set up at this reclining angle: 'tapping' with the same settings of Study 2 ('tapping'), 'tapping' with grading & uniform speed ('tapping' GU), 'tapping' with head shaking ('tapping' HS), 'chair rotating' with the same settings of Study 2 ('chair rotating'), 'chair rotating' with arc-trajectory ('chair rotating' AT), 'chair rotating' with turning gain ('chair rotating' TG). The design of the VR scenes was the same as in Study 2.

5.3 Procedure, Measurements, and Evaluation

The tasks, procedure, ethics measurements, and evaluation were the same as in Study 2. No one quit in this experiment. The experiment took about 1.5 hours including rest and interview. The participants got about 20$ cash for rewards.

5.4 Experiment Results

According to a Shapiro-Wilks test, data of some conditions were not normally distributed. Therefore, we used Friedman ANOVAs with pairwise Wilcoxon signed rank tests with Bonferroni correction for post hoc comparisons between conditions, resulting in a new significance level set at $p < 0.0166$ in post hoc comparisons.

5.4.1 Metrics of Perception and Overshoot. The results showed that different methods had significant effects on the perception tasks of distance ($\chi^2(2) = 17.301$, $p < 0.001$) and angle ($\chi^2(2) = 24.644$, $p < 0.001$), the moving accuracy & controllability ($\chi^2(2) = 10.609$, $p = 0.005$), yet no significant effect on turning accuracy & controllability task ($\chi^2(2) = 2.273$, $p = 0.321$). The boxplots of the perceived deviation percentages data, and the overshoot data were shown in Figure 7(a) to (d). Horizontal lines with p-values between conditions represented exist significant differences in post hoc comparisons. Overall, 'tapping' GU and 'chair rotating' TG performed best in spatial perception, and 'tapping' GU performed best in less overshoot.

5.4.2 Subjective Scales. The results showed that different methods had significant effects on Upright Motion Sense of moving ($\chi^2(2) = 32.000$, $p < 0.001$) and turning ($\chi^2(2) = 21.736$, $p < 0.001$), Presence of moving ($\chi^2(2) = 15.647$, $p < 0.001$), Ease of Control of moving ($\chi^2(2) = 13.378$, $p = 0.001$), Fatigue of moving ($\chi^2(2) = 10.291$, $p = 0.006$) and turning ($\chi^2(2) = 13.286$, $p = 0.001$), Motion Sickness of moving ($\chi^2(2) = 14.391$, $p = 0.001$) and turning ($\chi^2(2) = 16.593$, $p < 0.001$), while no significant effect on Presence and Ease of Control of turning. Figure 7(e) and (f) showed the boxplots of the data and significant differences with p-values between conditions of post hoc comparisons. Overall, 'tapping' HS and 'chair rotating' AT performed the best in natural upright motion sense; 'tapping' GU and 'chair rotating' TG performed the best in low fatigue; 'tapping' GU and 'chair rotating' AT performed the best in low motion sickness; 'tapping' HS and 'tapping' GU performed the best in strong presence and ease of control respectively.

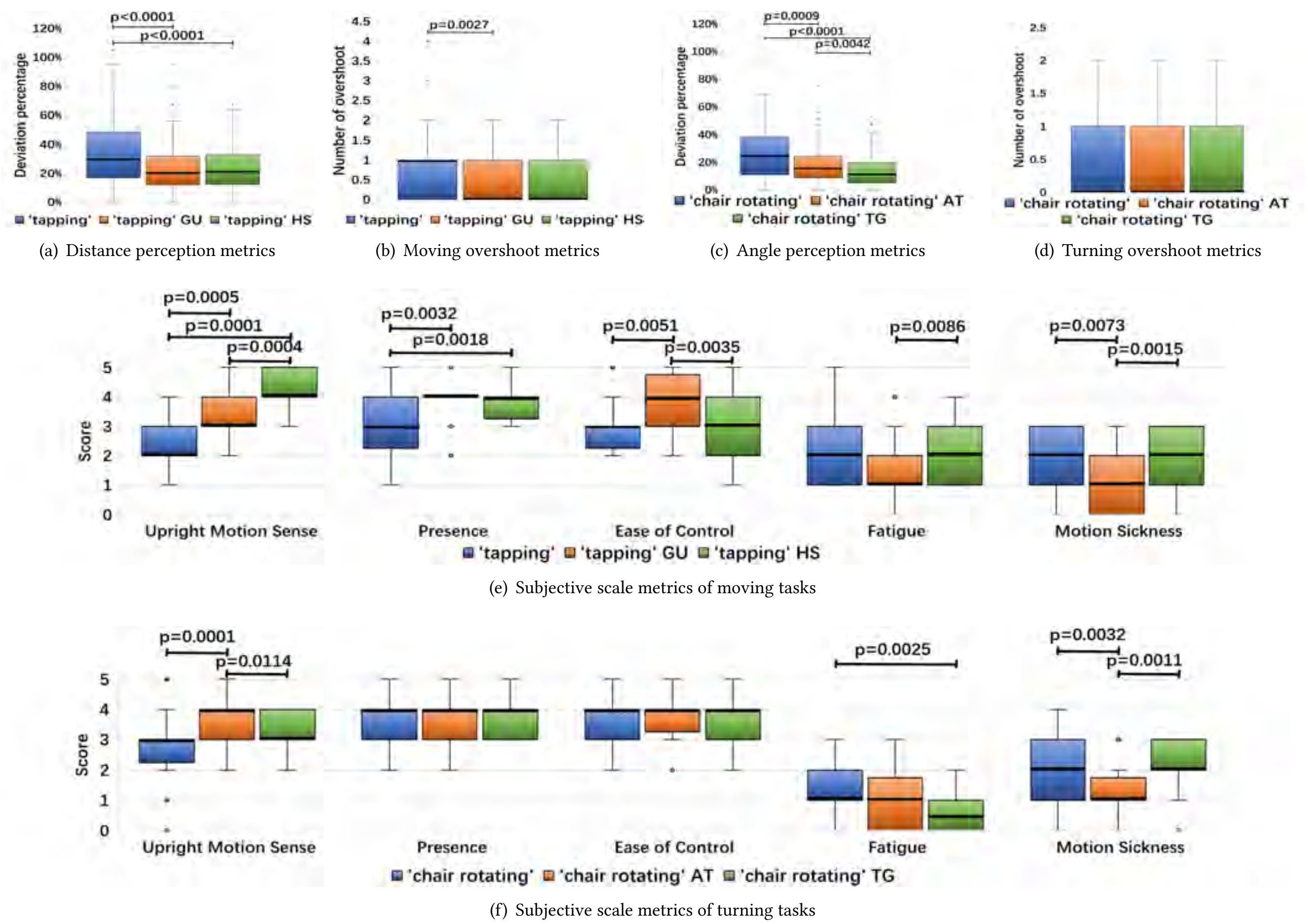
5.5 Discussion

Overall, we were glad to find that the 4 upgraded methods improved the participants' locomotion performances.

5.5.1 Analysis of Two Upgraded Methods for 'Tapping'. For 'tapping' GU, since the vestibular system was unable to distinguish between static and uniform motion, the visual uniform moving lessened the sensory conflicts, which improved the distance's perceived accuracy and reduced motion sickness. Physically, the participants needed not to focus on real-time speed control, neither the fast or slow 'tapping' actions which were tiring. Many participants (15 people, 75%) reported that the grading speed fulfilled their moving needs, and it was more natural and interesting. This was because different graded speeds and actions used different sporting metaphors. That was, when the calves were tilted back at a certain angle, the heels tapping with big lift height was similar to running, and the forefoot tapping had the action's resistance which was similar to rope bondage or walking in the swamp.

For 'tapping' HS, this method had two advantages. On the one hand, the head shaking cooperating with 'tapping' provided a natural vestibular stimulus, which was more in line with the walking experiences in life [47], and thus enhanced the upright motion sense and presence. On the other hand, we found that almost all participants (18 people, 90%) tended to tap their feet regularly with the fixed speed for making head-to-foot coordination easier, which indirectly achieved some benefits of uniform motion, such as improving the accuracy of distance perception. Moreover, since the chair provided head support, most participants (14 people, 70%) reported that it was easy and natural to act, so this method did not produce more fatigue and motion sickness compared to 'tapping'.

5.5.2 Analysis of Two Upgraded Methods for 'Chair Rotating'. For 'chair rotating' AT, this method visually matched the perceptive arc-shaped displacement of other senses, thereby improving the accuracy of angle perception and reducing motion sickness. Most participants (16 people, 80%) reported that their feelings were like upright walking in a circle, and the angle estimation seemed clearer and easier than 'chair rotating'. This was because sensorimotor matching further stimulated the upright locomotion illusion.



(a) Distance perception metrics

(b) Moving overshoot metrics

(c) Angle perception metrics

(d) Turning overshoot metrics

(e) Subjective scale metrics of moving tasks

(f) Subjective scale metrics of turning tasks

Figure 7: The results of the performances of the 4 upgraded locomotion methods

For 'chair rotating' TG, we used an extra turning angle to compensate for the revolution displacement. This special virtual-real mapping method produced the best angle perception accuracy among the three 'chair rotating' methods. Although some participants (5 people, 25%) reported that this method seemed to be dizzier, there was no significant difference from the previous method. Interestingly, the added turning gain in this method resulted in lower fatigue due to less physical turning and foot actions.

6 GENERAL DISCUSSION

Exploring suitable locomotion methods for reclining & lying settings and understanding the potential challenges and risks caused by upright redirection are valuable for the emerging and abundant VR use scenarios. We hope that the locomotion method set & user preferences (Study 1) and the upgraded strategy (Study 3) can inspire more studies on reclining & lying locomotion. Importantly, researchers can benefit from the general findings (Study 2), not only for learning the performances of 'tapping' and 'chair rotating', but also having a deeper understanding of how body angles & redirection angles affect locomotion methods.

6.1 Upright Redirection & Perceptive and Experiential Metrics

Due to the sensory conflict, we pay special attention to measure the general impacts of upright redirection on locomotion perceptive and experiential metrics. Although upright redirection helps users to get rid of abnormal views and get the feelings of standing in the scene to move and turn, it leads to sensorimotor conflicts and results in confused experiences (Study 1), and worse locomotion perceptive & experiential metrics than sitting position (Study 2). We found that the 45° reclining position performed worst on users' perceptive and experiential metrics, and we speculated that this was due to a combined effect of the redirection angle, the vestibular physiological features, and the upper-lower body angle (Study 2).

Not limited to 'tapping' and 'chair rotating', we analyze that the impact of upright redirection on the perceptive & experiential metrics and the different results among conditions can be generalized to other similar locomotion methods, as it is critical to design methods with similar sensorimotor stimuli (Study 1's Discussion) and conflict types (Study 2's Discussion). The perception mechanisms based on sensory integration behind the locomotion methods of the same class are similar.

For improving perceptive & experiential metrics, the design strategies in Study 3 can be applied to other locomotion methods as well. For example, we can use uniform motion to reduce motion sickness and fatigue and improve space perception, and use grading to switch between various uniform speeds to meet different navigation needs. We can also use easy head-shaking combined with other foot gestures that have walking metaphors to improve the self-motion sensation, and use gain to compensate for spatial perception deviations caused by sensorimotor conflicts.

6.2 Postures & Functional Metrics

We explored the impacts of reclining & lying positions on functions. Physical limitations led to difficulty and fatigue in the actions of body parts (rear arm, head, etc.) due to gravity and friction, resulting in restricted design space (Study 1). Leg/foot gestures had less fatigue and better controllability for users in reclining & lying positions than in sitting positions, as the upper body's pressure was dispersed by the reclining facility (Study 1 & 2).

Moreover, we found that many users liked to bend their knees in the feet-on-facility condition, and they elicited the same foot gestures as when they were in the feet-on-ground condition, such as 'tapping', 'walking-in-place', 'foot friction', etc. (Study 1). The calf-instep angle affected the height of the forefoot/heel lift (Study 2), and this could provide references for setting the best foot placement of other foot gestures with similar actions (e.g., 'accelerator pedal' [102]). On the one hand, users preferred dynamic locomotion methods (Study 1). On the other hand, most users preferred regular and fixed-speed actions for paying less effort (Study 2). This suggests that users liked a balance of self-motion feelings and effort.

For improving functional metrics, Study 3's design strategy could be also applied to other locomotion methods. For example, uniform speed and regular actions could improve dynamic gestures' controllability & accuracy; applying gain to the gestures could reduce the time of holding actions to reduce fatigue, etc.

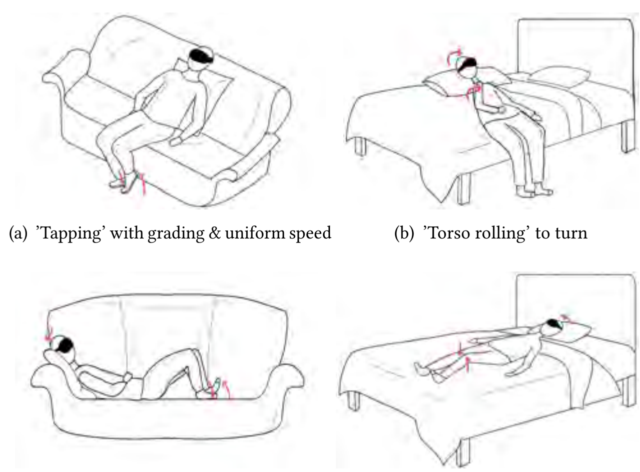
6.3 Suited Locomotion Methods

Suitable locomotion methods should consider user preferences, various metrics, and application scenarios.

Following the general findings of posture & redirection, designers are suggested to pay more attention to design leg/foot gestures. On the one hand, leg/foot gestures with daily locomotion metaphors and natural multi-sensory stimulation are considered to be the most efficient for reducing the negative impact of redirection (Study 1). On the other hand, leg/foot gestures can avoid the gorilla arm effect's fatigue of moving the rear arms, torso, etc. (Study 1), and they are easier to move in reclining & lying positions (Study 2). More importantly, designers shall try to improve the locomotion methods to make users have natural locomotion feelings & few motion sicknesses as well as low fatigue & good controllability, or to reach a good balance between the two aspects for (Study 3).

'Tapping' and 'chair rotating' were considered by users to be the very suitable and preferred moving and turning gestures respectively (Study 1), proved to work effectively by detailed evaluation (Study 2), and further iteratively upgraded (Study 3). Therefore, if the conditions allow, we recommend using the upgraded methods of 'tapping' and 'chair rotating' first.

When the conditions for swivelable reclining facility cannot be met (e.g., sofas and beds), we propose the following suggestions for different scenarios: We recommend that the feet be placed on the ground first if the condition allows and use upgraded 'tapping' to move (Figure 8(a)), and use the 'torso rolling' to turn (Figure 8(b)). According to Study 1, 'torso rolling' is derived from the metaphor of turning over, and it is the turning method with fourth most appearances and third most preferences. It is designed that the torso's left/right roll magnitude to reflect the view's turning angular velocity. We hypothesize that it also has good performances due to metaphor and natural vestibular-proprioceptive stimuli. When the feet can only be placed on reclining facility, we recommend using 'tapping' with head shaking (need to bend knees, as shown in Figure 8(c)) or 'knee tapping' with head shaking (not bend knees, as shown in Figure 8(d)) to move and using torso rolling to turning. Under this condition (C1, C4, C7 in Study 1), the counts of appearances (20) and preferences (12) for 'tapping' is still the most. 'Knee tapping'(two knees continue to tap alternately, left knee first tap represents go forward, and right knee first tap represents go backward) is the third most appearance count (14) in this condition and also provided strong proprioceptive stimuli with walking metaphors. We hypothesize that its performances are similar to 'tapping'.



(a) 'Tapping' with grading & uniform speed (b) 'Torso rolling' to turn

(c) 'Tapping' with head shaking (d) 'Knee tapping' with head shaking

Figure 8: Our recommended locomotion methods when users at application scenes with non-swivelable reclining facility

6.4 Combined Locomotion Methods

We did not elicit and evaluate combined moving & turning methods. Like many other studies, gestures were often proposed and experienced separately for moving or turning in user-elicitation studies [24, 80]. Moreover, moving/turning methods newly proposed or compared in new contexts were also often evaluated separately for measuring their independent performances [31, 68, 78]. In this paper, we additionally considered three important reasons: 1) Some VR applications require only moving methods or turning methods (e.g., 360° video). 2) 'Tapping' and 'chair rotating' represent two classes of locomotion methods with different sensorimotor stimuli and conflict types, thus it is more appropriate to evaluate them separately to measure the general effects of posture and redirection. 3) separate evaluation is beneficial to the flexible combination of these two methods with other methods in more conditions, e.g., when reclining facility is non-swivelable.

Interestingly, we observed that some participants could naturally use 'tapping' and 'chair rotating' at the same time for curved walking when they freely practiced the locomotion methods, e.g., first taking a step with left/right foot to the left/right (lift heel in the air and land on heel) to turn the chair towards left/right, then using the front foot to tap the ground, and repeating the above actions with the other foot.

Moreover, our tasks and metrics can reflect some performances of combined locomotion methods. For example, our many metrics are the same as combined methods' metrics such as overshoot, fatigue, motion sensation, etc. [30], this can intuitively reflect the combined methods' performances; typical spatial orientation task's performance (when reaching target, the users point out the direction to the starting position [63, 79, 103]) can be reflected by our distance & angle perception deviations; overshoot can also reflect other typical metrics such as environmental collision number [30, 103].

6.5 Limitations and Future Work

In all studies, the participants' number, uniformly young age, and university backgrounds may limit the results and findings of this paper to some extent. In Studies 2 and 3, we only explored typical locomotion methods and evaluated them on separate tasks & metrics. In the future, we will further explore more conditions and more top-ranked or interesting locomotion methods' performances, and the combined methods' performances on more metrics & tasks.

The analyses and inferences about the difference between conditions in Study 2 were based on prior theories without direct evidence. In the future, we need to find more evidence in the neuroscience field through further experiments to make our inferences more scientific. Some upgraded methods in Study 3 also have some limitations. For example, 'tapping' with the head shaking may make the user lose the ability to look around during moving. It may be better to use the power seat to automatically shake the user during the tapping action. 'Chair rotating' with a circular trajectory may increase the collision times with the virtual environment.

Moreover, locomotion in VR often comes with the risk of motion sickness, even without redirection. As a kind of redirection that can be perceived by users, upright redirection inevitably causes more motion sickness. However, due to our ethics and safety measure, all participants in the experiments did not appear severe motion sickness reactions such as vomiting/profusely sweating/uncomfortable expressions, etc. According to our post-experiment interviews, the strongest feelings of motion sickness were often described as the early stages of motion sickness in cars/boats/roller coasters. In addition, some upgrades methods such as 'tapping' GU and 'chair rotating' AT significantly reduced motion sickness, which made most participants have no or only mild motion sickness. In the future, we will try more effective strategies to reduce motion sickness and enhance the user's upright locomotion illusion, such as using noise currents to stimulate the vestibular system for reducing the vestibular reliability & sensory integration weight [61, 82], etc.

7 CONCLUSION

In the paper, we explored the locomotion methods for VR users in reclining & lying positions with upright redirected views, which raised challenges of both physical limitations and sensorimotor conflicts. In Study 1, we constructed a locomotion method set for different reclining & lying positions with upright redirected views, and discovered and analyzed the design features and users' preferences. In Study 2, by evaluating the two representative locomotion methods 'tapping' and 'chair rotating', we explored the general impacts of different postures and corresponding redirection on perceptive, experiential, and functional metrics. According to the results, we found the effects of different postures & redirection, and speculated on the physical and physiological reasons and the perception mechanism behind them. In Study 3, we improved the 'tapping' and 'chair rotating' based on Study 2's findings and proved that these upgraded methods were effective in enhancing the users' performances. We hope this work could inspire more research efforts on investigating suited interaction techniques for the emerging and abundant VR use scenarios, with special emphasis on users' sensorimotor integration and conflicts.

ACKNOWLEDGMENTS

We thank all who participated in the user study sections and those putting forward valuable suggestions during the writing and review process. This project was funded by the National Key R&D Program of China (2022ZD0118000) and the Natural Science Foundation of China (62132010).

REFERENCES

[1] Bart BGT Alberts, Luc PJ Selen, Giovanni Bertolini, Dominik Straumann, W Pieter Medendorp, and Alexander A Tarnutzer. 2016. Dissociating vestibular and somatosensory contributions to spatial orientation. *Journal of Neurophysiology* 116, 1 (2016), 30–40.

[2] Yangyi Ang, Puteri Suhaiza Sulaiman, Rahmita Wirza OK Rahmat, and Noris Mohd Norowi. 2019. Swing-in-place (SIP): a less fatigue walking-in-place method with side-viewing functionality for mobile virtual reality. *IEEE Access* 7 (2019), 183985–183995.

[3] Dora E Angelaki and Kathleen E Cullen. 2008. Vestibular system: the many facets of a multimodal sense. *Annual review of neuroscience* 31, 1 (2008), 125–150.

[4] Christopher R Austin, Barrett Ens, Kadek Ananta Satriadi, and Bernhard Jenny. 2020. Elicitation study investigating hand and foot gesture interaction for immersive maps in augmented reality. *Cartography and Geographic Information Science* 47, 3 (2020), 214–228.

[5] Niels H Bakker, Peter O Passenier, and Peter J Werkhoven. 2003. Effects of head-slaved navigation and the use of teleports on spatial orientation in virtual environments. *Human factors* 45, 1 (2003), 160–169.

[6] Rena Bayramova, Irene Valori, Phoebe E McKenna-Plumley, Claudio Zandonella Callegher, and Teresa Farroni. 2021. The role of vision and proprioception in self-motion encoding: An immersive virtual reality study. *Attention, Perception, & Psychophysics* 83, 7 (2021), 2865–2878.

[7] AJ Benson. 1990. Sensory functions and limitations of the vestibular system. *Perception and control of self-motion* (1990), 145–170.

[8] Tomislav Bezmalinovic. 2023. Quest 2 could get a "laying down mode" for more laid-back VR. https://mixed-news.com/en/you-can-finally-lie-down-while-wearing-quest-2/. (2023).

[9] Norbert Bischof and Eckart Scheerer. 1970. Systems analysis of optic-vestibular interaction in the perception of verticality. *Psychologische Forschung* (1970).

[10] Stéphane Bouchard, Geneviéve Robillard, Julie St-Jacques, Stéphanie Dumoulin, Marie-Josée Patry, and Patrice Renaud. 2004. Reliability and validity of a single-item measure of presence in VR. In *The 3rd IEEE international workshop on haptic, audio and visual environments and their applications*. IEEE, 59–61.

[11] Doug A Bowman, David Koller, and Larry F Hodges. 1997. Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality*. IEEE, 45–52.

[12] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 annual symposium on computer-human interaction in play*. 205–216.

[13] Helmut Buhler, Sebastian Misztal, and Jonas Schild. 2018. Reducing vr sickness through peripheral visual effects. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 517–9.

[14] Chenyang Cai, Jian He, and Tianren Luo. 2023. Using Redirection to Create a Swimming Experience in VR for the Sitting Position. In *Companion Proceedings of the 28th International Conference on Intelligent User Interfaces*. 68–71.

[15] Jennifer L Campos, John S Butler, and Heinrich H Bülthoff. 2012. Multisensory integration in the estimation of walked distances. *Experimental brain research* 218, 4 (2012), 551–565.

[16] Zhixian Cheng and Yong Gu. 2018. Vestibular system and self-motion. *Frontiers in Cellular Neuroscience* 12 (2018), 456.

[17] Jeremy Clifton and Stephen Palmisano. 2020. Effects of steering locomotion and teleporting on cybersickness and presence in HMD-based virtual reality. *Virtual Reality* 24, 3 (2020), 453–468.

[18] Noah Coomer, Sadler Bullard, William Clinton, and Betsy Williams-Sanders. 2018. Evaluating the effects of four VR locomotion methods: joystick, arm-cycling, point-tugging, and teleporting. In *Proceedings of the 15th ACM symposium on applied perception*. 1–8.

[19] Volker Dietz. 2002. Proprioception and locomotor disorders. *Nature Reviews Neuroscience* 3, 10 (2002), 781–790.

[20] Zhi-Chao Dong, Xiao-Ming Fu, Zeshi Yang, and Ligang Liu. 2019. Redirected smooth mappings for multiuser real walking in virtual reality. *ACM Transactions on Graphics (TOG)* 38, 5 (2019), 1–17.

[21] Marc O Ernst and Martin S Banks. 2002. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature* 415, 6870 (2002), 429–433.

[22] Marc O Ernst and Heinrich H Bülthoff. 2004. Merging the senses into a robust percept. *Trends in cognitive sciences* 8, 4 (2004), 162–169.

[23] Linwei Fan, Huiyu Li, and Miaowen Shi. 2022. Redirected Walking for Exploring Immersive Virtual Spaces with HMD: A Comprehensive Review and Recent Advances. *IEEE Transactions on Visualization and Computer Graphics* (2022).

[24] Yasmin Felberbaum and Joel Lanir. 2018. Better understanding of foot gestures: An elicitation study. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.

[25] Carlo Flemming, Benjamin Weyers, and Daniel Zielasko. 2022. How to Take a Brake from Embodied Locomotion–Seamless Status Control Methods for Seated Leaning Interfaces. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 728–736.

[26] Marsha E Fonteyn, Benjamin Kuipers, and Susan J Grobe. 1993. A description of think aloud method and protocol analysis. *Qualitative health research* 3, 4 (1993), 430–441.

[27] Reginaldo K Fukuchi, Claudiane A Fukuchi, and Marcos Duarte. 2017. A public dataset of running biomechanics and the effects of running speed on lower extremity kinematics and kinetics. *PeerJ* 5 (2017), e3298.

[28] Markus Funk, Florian Müller, Marco Fendrich, Megan Shene, Moritz Kolvenbach, Niclas Dobbertin, Sebastian Günther, and Max Mühlhäuser. 2019. Assessing the accuracy of point & teleport locomotion with orientation indication for virtual reality using curved trajectories. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–12.

[29] Priya Ganapathi and Keyur Sorathia. 2019. Elicitation study of body gestures for locomotion in HMD-VR interfaces in a sitting-position. In *Motion, interaction and games*. 1–10.

[30] Boyu Gao, Zijun Mai, Huawei Tu, and Henry Duh. 2022. Effects of Transfer Functions and Body Parts on Body-centric Locomotion in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* (2022).

[31] BoYu Gao, Zijun Mai, Huawei Tu, and Henry Been-Lirn Duh. 2021. Evaluation of Body-centric Locomotion with Different Transfer Functions in Virtual Reality. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. IEEE, 493–500.

[32] John F Golding. 2006. Motion sickness susceptibility. *Autonomic Neuroscience* 129, 1-2 (2006), 67–76.

[33] Emilie Guy, Parinya Punpongsanon, Daisuke Iwai, Kosuke Sato, and Tamy Boubekeur. 2015. LazyNav: 3D ground navigation with non-critical body parts. In *2015 IEEE symposium on 3D user interfaces (3DUI)*. IEEE, 43–50.

[34] Abraham Hashemian, Matin Lotfaliei, Ashu Adhikari, Ernst Kruijff, and Bernhard Riecke. 2020. HeadJoystick: Improving Flying in VR using a Novel Leaning-Based Interface. *IEEE Transactions on Visualization and Computer Graphics* (2020).

[35] Errol R Hoffmann. 1991. A comparison of hand and foot movement times. *Ergonomics* 34, 4 (1991), 397–406.

[36] Han Hou, Qihao Zheng, Yuchen Zhao, Alexandre Pouget, and Yong Gu. 2019. Neural correlates of optimal multisensory decision making under time-varying reliabilities with an invariant linear probabilistic population code. *Neuron* 104, 5 (2019), 1010–1021.

[37] Rachel Huang, Carisa Harris-Adamson, Dan Odell, and David Rempel. 2019. Design of finger gestures for locomotion in virtual reality. *Virtual Reality & Intelligent Hardware* 1, 1 (2019), 1–9.

[38] Hideki Kawai, Hiroki Hara, and Yasuyuki Yanagida. 2018. Effect of change of head angle on visual horizontal plane. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. 1–2.

[39] Hideki Kawai, Hiroki Hara, and Yasuyuki Yanagida. 2018. Effect of reclining angle on the perception of horizontal plane for hmd users. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 599–600.

[40] Julian Keil, Dennis Edler, Denise O'Meara, Annika Korte, and Frank Dickmann. 2021. Effects of virtual reality locomotion techniques on distance estimations. *ISPRS International Journal of Geo-Information* 10, 3 (2021), 150.

[41] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology* 3, 3 (1993), 203–220.

[42] Behrang Keshavarz and Heiko Hecht. 2011. Validating an efficient method to quantify motion sickness. *Human factors* 53, 4 (2011), 415–426.

[43] Woojoo Kim, Eunsik Shin, and Shuping Xiong. 2021. User Defined Walking-In-Place Gestures for Intuitive Locomotion in Virtual Reality. In *International Conference on Human-Computer Interaction*. Springer, 172–182.

[44] Alexandra Kitson, Abraham M Hashemian, Ekaterina R Stepanova, Ernst Kruijff, and Bernhard E Riecke. 2017. Comparing leaning-based motion cueing interfaces for virtual reality locomotion. In *2017 IEEE Symposium on 3d user interfaces (3DUI)*. IEEE, 73–82.

[45] Jan J Koenderink. 1986. Optic flow. *Vision research* 26, 1 (1986), 161–179.

[46] Elena Kokkinara, Konstantina Kilteni, Kristopher J Blom, and Mel Slater. 2016. First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking. *Scientific reports* 6, 1 (2016), 1–11.

[47] Elena Kokkinara, Konstantina Kilteni, Kristopher J Blom, and Mel Slater. 2016. First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking. *Scientific reports* 6, 1 (2016), 1–11.

[48] Francesco Lacquaniti, Gianfranco Bosco, Silvio Gravano, Iole Indovina, Barbara La Scaleia, Vincenzo Maffei, and Myrka Zago. 2014. Multisensory integration and internal models for sensing gravity effects in primates. *BioMed research international* 2, 3 (2014), 124–132.

[49] Markus Lappe, Frank Bremmer, and AV Van den Berg. 1999. Perception of self-motion from visual flow. *Trends in cognitive sciences* 3, 9 (1999), 329–336.

[50] William B Lathrop and Mary K Kaiser. 2002. Perceived orientation in physical and virtual environments: Changes in perceived orientation as a function of idiothetic information available. *Presence* 11, 1 (2002), 19–32.

[51] Juyoung Lee, Sang Chul Ahn, and Jae-In Hwang. 2018. A walking-in-place method for virtual reality using position and orientation tracking. *Sensors* 18, 9 (2018), 2832.

[52] Jong-In Lee, Paul Asente, Byungmoon Kim, Yeojin Kim, and Wolfgang Stuerzlinger. 2020. Evaluating Automatic Parameter Control Methods for Locomotion in Multiscale Virtual Environments. In *26th ACM Symposium on Virtual Reality Software and Technology*. 1–10.

[53] Koeun Lim, Faisal Karmali, Keyvan Nicoucar, and Daniel M Merfeld. 2017. Perceptual precision of passive body tilt is consistent with statistically optimal cue integration. *Journal of neurophysiology* 117, 5 (2017), 2037–2052.

[54] Christophe Lopez, Christelle Bachofner, Manuel Mercier, and Olaf Blanke. 2009. Gravity and observer's body orientation influence the visual perception of human body postures. *Journal of vision* 9, 5 (2009), 1–1.

[55] Jijian Lu, Tianren Luo, Mingmin Zhang, Yuze Shen, Peng Zhao, Ning Cai, Xiaozhe Yang, Zhigeng Pan, and Max Stephens. 2022. Examining the impact of VR and MR on future teachers' creativity performance and influencing factors by scene expansion in instruction designs. *Virtual Reality* 26, 4 (2022), 1615–1636.

[56] Tianren Luo, Ning Cai, Zheng Li, Zhigeng Pan, and Qingshu Yuan. 2020. VR-DLR: a serious game of somatosensory driving applied to limb rehabilitation training. In *Entertainment Computing–ICEC 2020: 19th IFIP TC 14 International Conference, ICEC 2020, Xi'an, China, November 10–13, 2020, Proceedings 19*. Springer, 51–64.

[57] Tianren Luo, Kezheng Chen, Mengjun Liu, Kang Sun, Jili Xu, and Zhigeng Pan. 2018. Design and implementation of interactive VR campus roaming system. In *2018 International Conference on Virtual Reality and Visualization (ICVRV)*. IEEE, 122–123.

[58] Tianren Luo, Zhenxuan He, Chenyang Cai, Teng Han, Zhigeng Pan, and Feng Tian. 2022. Exploring Sensory Conflict Effect Due to Upright Redirection While Using VR in Reclining & Lying Positions. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 1–13.

[59] Tianren Luo, Mingmin Zhang, Zhigeng Pan, Zheng Li, Ning Cai, Jinda Miao, Youbin Chen, and Mingxi Xu. 2020. Dream-experiment: a MR user interface with natural multi-channel interaction for virtual experiments. *IEEE Transactions on Visualization and Computer Graphics* 26, 12 (2020), 3524–3534.

[60] Vito M Manghisi, Antonio E Uva, Michele Fiorentino, Michele Gattullo, Antonio Boccaccio, and Giuseppe Monno. 2018. Enhancing user engagement through the user centric design of a mid-air gesture-based interface for the navigation

of virtual-tours in cultural heritage expositions. *Journal of cultural heritage* 32 (2018), 186–197.

[61] Keigo Matsumoto, Kazuma Aoyama, Takuji Narumi, and Hideaki Kuzuoka. 2021. Redirected Walking using Noisy Galvanic Vestibular Stimulation. In *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 498–507.

[62] Jesus Mayor, Laura Raya, and Alberto Sanchez. 2019. A Comparative Study of Virtual Reality Methods of Interaction and Locomotion Based on Presence, Cybersickness, and Usability. *IEEE Transactions on Emerging Topics in Computing* 9, 3 (2019), 1542–1553.

[63] Morgan McCullough, Hong Xu, Joel Michelson, Matthew Jackoski, Wyatt Pease, William Cobb, William Kalescky, Joshua Ladd, and Betsy Williams. 2015. Myo arm: swinging to explore a VE. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*. 107–113.

[64] The Binary Mill. 2019. Mini Motor Racing X. https://www.thebinarymill.com/mini_motor_racing_x.php. (2019).

[65] Jeannette Montufar, Jorge Arango, Michelle Porter, and Satoru Nakagawa. 2007. Pedestrians' normal walking speed and speed when crossing a street. *Transportation research record* 2002, 1 (2007), 90–97.

[66] Brandy Murovec, Julia Spaniol, Jennifer L Campos, and Behrang Keshavarz. 2021. Multisensory Effects on Illusory Self-Motion (Vection): the Role of Visual, Auditory, and Tactile Cues. *Multisensory Research* 34, 8 (2021), 869–890.

[67] Niels Christian Nilsson, Stefania Serafin, Frank Steinicke, and Rolf Nordahl. 2018. Natural walking in virtual reality: A review. *Computers in Entertainment (CIE)* 16, 2 (2018), 1–22.

[68] Yoshikazu Onuki and Itsuo Kumazawa. 2019. Reorient the gazed scene towards the center: Novel virtual turning using head and gaze motions and blink. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 1864–1871.

[69] Zhigeng Pan, Tianren Luo, Mingmin Zhang, Ning Cai, Yongheng Li, Jinda Miao, Zheng Li, Zhipeng Pan, Yuze Shen, and Jijian Lu. 2022. MagicChem: a MR system based on needs theory for chemical experiments. *Virtual Reality* 26, 1 (2022), 279–294.

[70] Christian Pfeiffer, Christophe Lopez, Valentin Schmutz, Julio Angel Duenas, Roberto Martuzzi, and Olaf Blanke. 2013. Multisensory origin of the subjective first-person perspective: visual, tactile, and vestibular mechanisms. *PloS one* 8, 4 (2013), e61751.

[71] Michael M Popp, Edna Platzer, Matthias Eichner, and Marion Schade. 2004. Walking with and without walking: Perception of distance in large-scale urban areas in reality and in virtual reality. *Presence: Teleoperators & Virtual Environments* 13, 1 (2004), 61–76.

[72] Lisa Rebenitsch and Charles Owen. 2016. Review on cybersickness in applications and visual displays. *Virtual Reality* 20, 2 (2016), 101–125.

[73] Reuben Rideaux, Katherine R Storrs, Guido Maiello, and Andrew E Welchman. 2021. How multisensory neurons solve causal inference. *Proceedings of the National Academy of Sciences* 118, 32 (2021).

[74] Bernhard E Riecke, Jacob B Freiberg, and Timofey Y Grechkin. 2015. Can walking motions improve visually induced rotational self-motion illusions in virtual reality? *Journal of Vision* 15, 2 (2015), 3–3.

[75] Michael Rietzler, Martin Deubzer, Thomas Dreja, and Enrico Rukzio. 2020. Telewalk: Towards free and endless walking in room-scale virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–9.

[76] Michael Rietzler, Florian Geiselhart, Jan Gugenheimer, and Enrico Rukzio. 2018. Breaking the tracking: Enabling weight perception using perceivable tracking offsets. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.

[77] Roy A Ruddle and Simon Lessels. 2006. For efficient navigational search, humans require full physical movement, but not a rich visual scene. *Psychological science* 17, 6 (2006), 460–465.

[78] Shyam Prathish Sargunam and Eric D Ragan. 2018. Evaluating joystick control for view rotation in virtual reality with continuous turning, discrete turning, and field-of-view reduction. In *Proceedings of the 3rd International Workshop on Interactive and Spatial Computing*. 74–79.

[79] Bhuvaneswari Sarupuri, Simon Hoermann, Frank Steinicke, and Robert W Lindeman. 2017. Triggerwalking: a biomechanically-inspired locomotion user interface for efficient realistic virtual walking. In *Proceedings of the 5th symposium on spatial user interaction*. 138–147.

[80] Xinyu Shi, Junjun Pan, Zeyong Hu, Juncong Lin, Shihui Guo, Minghong Liao, Ye Pan, and Ligang Liu. 2019. Accurate and fast classification of foot gestures for virtual locomotion. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 178–189.

[81] Andrew JJ Smith and Edward D Lemaire. 2018. Temporal-spatial gait parameter models of very slow walking. *Gait & posture* 61 (2018), 125–129.

[82] Misha Sra, Abhinandan Jain, and Pattie Maes. 2019. Adding proprioceptive feedback to virtual reality experiences using galvanic vestibular stimulation. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–14.

[83] Meta Technologies. 2022. Oculus Quest 2. https://www.oculus.com/quest-2/. (2022).

[84] Wit-Motion Technologies. 2022. Wit-motion Wireless IMUs. https://www.wit-motion.com/. (2022).

[85] Meta technology. 2022. Oculus casting to a screen. https://www.oculus.com/casting. (2022).

[86] Léo Terziman, Maud Marchal, Mathieu Emily, Franck Multon, Bruno Arnaldi, and Anatole Lécuyer. 2010. Shake-your-head: Revisiting walking-in-place for desktop virtual reality. In *Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology*. 27–34.

[87] Sebastian Thorp, Alexander Sævild Ree, and Simone Grassini. 2022. Temporal Development of Sense of Presence and Cybersickness during an Immersive VR Experience. *Multimodal Technologies and Interaction* 6, 5 (2022), 31.

[88] Meta Community Forums user: GrangerFX. 2021. Reclining mode is needed. https://forums.oculusvr.com/t5/Ideas/Reclining-mode-is-needed/idi-p/898575. (2021).

[89] Reddit user: lawgeek. 2021. What are some good apps to play reclining or lying down? https://www.reddit.com/r/OculusQuest/comments/onm2jp/what_are_some_good_apps_to_play_reclining_or/. (2021).

[90] Guillaume Vailland, Yoren Gaffary, Louise Devigne, Valérie Gouranton, Bruno Arnaldi, and Marie Babel. 2020. Vestibular feedback on a virtual reality wheelchair driving simulator: A pilot study. In *Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction*. 171–179.

[91] Joy Van Baren. 2004. Measuring presence: A guide to current measurement approaches. *Deliverable of the OmniPres project IST-2001-39237* (2004).

[92] Thomas van Gemert, Kasper Hornbæk, Jarrod Knibbe, and Joanna Bergström. 2023. Towards a Bedder Future: A Study of Using Virtual Reality while Lying Down. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–18.

[93] Radu-Daniel Vatavu and Jacob O Wobbrock. 2015. Formalizing agreement analysis for elicitation studies: new measures, significance test, and toolkit. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 1325–1334.

[94] Rens Adriaan Anton Vingerhoets, Maaike De Vrijer, Jan AM Van Gisbergen, and W Pieter Medendorp. 2009. Fusion of visual and vestibular tilt cues in the perception of visual vertical. *Journal of neurophysiology* 101, 3 (2009), 1321–1333.

[95] Panagiotis Vogiatzidakis and Panayiotis Koutsabasis. 2018. Gesture elicitation studies for mid-air interaction: A review. *Multimodal Technologies and Interaction* 2, 4 (2018), 65.

[96] Jeremy D Wendt, Mary C Whitton, and Frederick P Brooks. 2010. Gud wip: Gait-understanding-driven walking-in-place. In *2010 IEEE Virtual Reality Conference (VR)*. IEEE, 51–58.

[97] Preston Tunnell Wilson, William Kalescky, Ansel MacLaughlin, and Betsy Williams. 2016. VR locomotion: walking> walking in place> arm swinging. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry-Volume 1*. 243–249.

[98] Dennis Wolf, Katja Rogers, Christoph Kunder, and Enrico Rukzio. 2020. Jumpvr: Jump-based locomotion augmentation for virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[99] Lucy Yardley. 1990. Contribution of somatosensory information to perception of the visual vertical with body tilt and rotating visual field. *Perception & Psychophysics* 48, 2 (1990), 131–134.

[100] André Zenner and Antonio Krüger. 2019. Estimating detection thresholds for desktop-scale hand redirection in virtual reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 47–55.

[101] Daniel Zielasko, Jonas Heib, and Benjamin Weyers. 2022. Systematic Design Space Exploration of Discrete Virtual Rotations in VR. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 693–702.

[102] Daniel Zielasko, Sven Horn, Sebastian Freitag, Benjamin Weyers, and Torsten W Kuhlen. 2016. Evaluation of hands-free HMD-based navigation techniques for immersive data analysis. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 113–119.

[103] Daniel Zielasko, Yuen C Law, and Benjamin Weyers. 2020. Take a look around–the impact of decoupling gaze and travel-direction in seated and ground-based virtual reality utilizing torso-directed steering. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 398–406.

[104] Daniel Zielasko and Bernhard E Riecke. 2021. To sit or not to sit in vr: Analyzing influences and (dis) advantages of posture and embodied interaction. *Computers* 10, 6 (2021), 73.