Exploring Experience Gaps Between Active and Passive Users During Multi-user Locomotion in VR

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(a) Multi-user driving (b) Group navigation (c) Experience sharing

Figure 1: Typical VR scenes of multi-user co-locomotion, in which active and passive users have different locomotion experiences.

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ABSTRACT

Multi-user locomotion in VR has grown increasingly common, posing numerous challenges. A key factor contributing to these challenges is the gaps in experience between active and passive users during co-locomotion. Yet, there remains a limited understanding of how and to what extent these experiential gaps manifest in diverse multi-user co-locomotion scenarios. This paper systematically explores the gaps in physiological and psychological experience

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indicators between active and passive users across various locomotion situations. Such situations include when active users walk, fly by joystick, or teleport, and passive users stand still or look around. We also assess the impact of factors such as sub-locomotion type, speed/teleport-interval, motion sickness susceptibility, etc. Accordingly, we delineate acceptability disparities between active and passive users, offering insights into leveraging notable experimental findings to mitigate discomfort during co-locomotion through avoidance or intervention.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **User studies**.

KEYWORDS

multi-user VR, locomotion experience, experience gap, sensory conflict

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1 INTRODUCTION

With the increasing accessibility of VR devices and applications, multi-user activities and experiences in immersive environments have gained significant attention in recent years. Co-locomotion in VR as an essential multi-user interaction refers to the collective movement or navigation of a group of users within a virtual environment and the method in a way that one user pilots the application (identified as active user) and the others act as passengers (identified as passive users) is of special interest. It is commonly used in applications such as multiplayer games, team-based experiences or training simulations, and virtual meetings, where participants can engage in group locomotion to explore virtual worlds, gather in specific areas, practice teamwork, coordinate actions, and interact with each other in a more dynamic and immersive manner. Concrete example scenarios include driving teammates in multi-player open-world games (Figure 1(a)), tourist guiding while traveling in VR [99, 100] (Figure 1(b)), and VR broadcasting to online audiences in games or sports [95] (Figure 1(c)). Such co-locomotion has two benefits. On the one hand, handing over motion control to others can help passive users save their time and physical consumed in navigation and focus more on other interactive tasks. On the other hand, active users as tour guides, experience sharers, etc. can remove the need to coordinate routes and check for stragglers. However, co-locomotion poses distinctive challenges in experience gaps between active and passive users. Specifically, problems of sensory conflicts while locomoting in VR become more pronounced in passive views, as in comparison to actively controlling locomotion, passive users cannot anticipate their next movement or rotation, resulting in a disconnection between input intention and output feedback [75]; the disparities between various locomotion methods employed by the active user and the various superimposed locomotion of the passive user (e.g., standing still [72], looking around [34]) may further widen the experience gaps between active and the passive users.

Human locomotion is often accompanied by a complex sensorimotor integration process [5]. During this process, the brain dynamically assigns different weights to visual, vestibular, and proprioceptive signals [60]: the more reliable the sensory signal is received, the higher the weight it will get [28, 29, 45]. Ultimately, the brain optimizes sensory information by taking into account locomotion intention and life experience, etc., to enhance cognitive accuracy [59, 76]. VR locomotion is usually accompanied by sensory conflicts, especially employing the inappropriate locomotion method, such sensory conflict has been shown to disrupt users' spatial awareness, fun, self-motion feeling, and presence, and cause motion sickness, and its level is closely related to the locomotion form [11, 62, 79]. For example, physical walking without sensory conflict has better locomotion experience than gestures or joystick locomotion that lacks vestibular stimulation [69, 80]; various locomotion types (e.g., translation and rotation), directions, speeds, and individual differences significantly affect sensory conflict and locomotion experience [17, 18, 35, 88]. The prior research explored the effects of diverse sensory stimuli and types of sensory conflicts on locomotion experiences[31, 54, 62, 105]. However, it missed the opportunity to investigate the intriguing influence of sensory conflicts in different locomotion scenarios between active and passive users in co-locomotion experiences. The aforementioned experience gap is not conducive to the harmony of the team and the efficiency of cooperative tasks, and even weakens the motivation of users to participate in co-locomotion. Therefore, it is crucial to define the experience gap between active and passive users in various co-locomotion situations.

In our user study, we paired the active and passive users according to their motion sickness susceptibility (MSS). We set 6 conditions according to the locomotion methods of the active user (walking, flying joystick, and teleportation) and the possible behaviors of the passive user (standing still and looking around). In each condition, we extracted the possible independent actions of the active/passive user during the complete locomotion as sub-locomotion (e.g., one translation/rotation for the active user, or one standing-still/looking-around action for the passive user). We combined these sub-locomotions to create a series of locomotion nodes, focusing on those with significant temporary experience gaps. These nodes serve as noteworthy/avoidable/intervenable situations, providing insights into the overall experience gap attribution in a condition, as it accumulates from a series of temporary experiences. We investigated the 5 subjective indicators of physiological comfort (i.e., discomfort feelings such as dizziness, nausea, and eye discomfort are weak), psychological comfort (i.e., discomfort feelings such as fear, uneasiness, and strange are weak), presence (i.e., users believe that they exist in the virtual world), locomotion sensation (i.e., the users believe they are at locomotion state presented in view), and acceptability (i.e., users can accept the comprehensive feeling of such locomotion and are willing to experience it frequently in future co-locomotion) of each locomotion node, as well as the overall feeling after experiencing all nodes in each condition through three subjective post-measurement questionnaires. Ultimately, our analysis considered the impact of different conditions, sub-locomotion combinations, speed, and MSS on experience gaps, identifying locomotion situations deemed unacceptable for active or passive users.

Generally, passive users had a worse experience than active users, with conditions involving active users using teleportation for discrete motion and passive users standing still often having smaller experience gaps; conditions and sub-locomotion combinations involving passive users looking around usually had larger experience gaps. Notably, the sensory gap was particularly pronounced in sub-locomotion combinations where active users turned while passive users looked around. Interestingly, when the active user's translation and the passive user's head rotation were in similar directions, the presence and locomotion sensation of the passive user even surpassed that of the active user. We speculated that these outcomes arose from the combined impact of differences in sensory conflict types and levels, and locomotion intention between active and passive users. Measuring such experience gaps can offer 3 noteworthy research implications: 1) understanding the differences of experience gaps between various co-locomotion situations and providing a valuable reference for the design of VR multi-user applications; 2) providing guidance for avoiding/intervening in possible behaviors that may lead to uncomfortable experiences during multi-user co-locomotion; 3) contributing to a deeper understanding of how the human perceptual system responds to various co-locomotion scenarios. To the best of our knowledge, this study is the first to comprehensively examine the gaps in experiences between active and passive users across diverse co-locomotion scenarios, encompassing different sensory conflict types and levels, especially in temporary experience gaps of sub-locomotion combinations. This paper makes the following three contributions:

i) Defining typical co-locomotion situations in multi-user VR applications, along with relevant influencing factors.

ii) Systematically exploring the experience gaps between active and passive users across diverse locomotion conditions and sub-locomotion combinations, as well as the effects of various factors on these gaps, and analyzing the possible reasons based on the knowledge of sensorimotor integration.

iii) Identifying co-locomotion situations worthy of noting, avoidance and intervention based on differences in acceptability between active and passive users.

2 RELATED WORK

2.1 Single-user Locomotion

The VR single-user locomotion methods and experiences have been extensively studied. Single-user locomotion is typically categorized into active and passive locomotion based on the control ability [77].

For active locomotion, users control locomotion through embodied or artificial methods [8, 13]. Embodied methods, like torso leaning[40, 104], head shaking[89], tapping [68], head joystick [41], swimming[14], and walking-in-place [56, 101], provide natural proprioceptive and vestibular stimuli [30, 31]. Various artificial locomotion methods, including steering wheel/joystick with driving metaphors and teleportation, offer alternatives. Joystick and steering wheel methods are considered effort-saving but may lead to sensory conflicts affecting spatial awareness and motion sickness [3, 54, 63, 105]. Teleportation, by instantly changing the self-position, reduces sensory conflict by avoiding continuous locomotion [11, 33]. Additionally, manual/automatic control of locomotion [57] as well as body avatars [81] also contribute to the locomotion experience.

Passive locomotion is less explored than active ones, and typically involves users watching VR content like movies/360° videos, following preset routes, or using VR in cars [38, 39, 43, 72, 78]. Limited in locomotion abilities, passive users mainly stand still, look around, or engage in in-place tasks like reading [34, 72, 77]. Passive locomotion is prone to greater motion sickness due to sensory conflict and unpredictable locomotion [61].

These studies inspired the motivation and setting of our experimental conditions. Notably, widely used single-user locomotion methods, such as walking, flying joystick, and teleportation in active locomotion, and static and looking around in passive locomotion, are expected to feature in future multi-user co-locomotion scenarios. Additionally, the diverse sensory conflicts associated with these locomotion methods prompt an exploration of the varying experience gaps resulting from different combinations of active and passive locomotion methods and behaviors.

2.2 Multi-user Locomotion

Unlike the extensively studied single-user locomotion, multi-user locomotion remains a niche area, with recent research developments. One straightforward approach involves allowing each user to navigate independently [58]. In this mode, where there are no passive users, research typically centers on collision avoidance as multiple active users navigate concurrently [2]. Strategies include dynamically redirecting walking paths to prevent collisions [24, 44, 58]. An alternative approach involves passive users delegating locomotion control rights to active users for co-locomotion. This enhances coordination, minimizes interference from passive users, and decreases the risk of falling behind, as suggested by Weissker et al. in their overview[97].

Existing research on this co-locomotion mode typically focuses on three aspects. First, innovative group locomotion methods aim to enhance user locomotion experiences, such as employing group teleportation with formation control to avoid collisions in virtual environments [99], using handshake metaphors for flexible user binding [98], and implementing "magic carpet" combining ground agents with full-body representation for realistic flying [66]. Second, social methods are designed to improve communication of locomotion intentions between users, including visualizing shared locomotion intent [74] and utilizing multi-ray jumping techniques [96]. However, for large or dynamic scenes requiring frequent locomotion, pre-communicating intentions before each sub-locomotion incurs high communication costs and reduces navigation efficiency. Third, some studies record first-person driving videos of active users, playing them back to passive users to simulate synchronized multi-user co-locomotion [15, 16, 21]. Our study employs a similar approach to separately evaluate active and passive users in simulating synchronized co-locomotion. However, these studies primarily evaluate the effect of locomotion intention on motion sickness induction time, and the video format restricts the action ability of passive users such as looking around.

In this paper, our focus is on evaluating existing co-locomotion methods rather than introducing new ones, driven by two key reasons. Firstly, both new and established co-locomotion methods share a similar perception mechanism causing experience gaps. Therefore, understanding these gaps, their causes, and the limitations of existing methods is crucial for refining old methods or proposing new ones. Secondly, current research on VR co-locomotion lacks comprehensive consideration of influencing factors beyond intention and evaluation indicators beyond motion sickness. Consequently, our study explores a broader range of conditions and emphasizes the impact of sensorimotor conflict, incorporating diverse experience indicators.

2.3 Motion Sickness

Motion sickness frequently occurs during both actual and virtual locomotion, manifesting symptoms such as dizziness, sweating, eye discomfort, and vomiting. Currently, three theories explain the mechanism of motion sickness: postural instability theory [86], poison theory [92], and sensory conflict theory [51]. The most widely accepted is the sensory conflict theory, suggesting that the brain struggles to process mismatched locomotion status information perceived by multiple senses, leading to uncomfortable physiological reactions [46, 55, 64]. This theory serves as the basis in this paper for explaining the causes of motion sickness and temporary physiological discomfort.

Motion sickness levels are influenced by various factors. The type of locomotion method affects the onset time and severity of motion sickness; for instance, continuous visual motion induces higher motion sickness than discrete visual motion [65]. Additionally, passive motion is more likely to cause motion sickness than active motion [84]. The types and parameters of sub-locomotion, including rotation/translation, motion direction, multi-axis/single-axis, oscillation/non-oscillation, high-speed/low-speed, long-time/short-time, etc., also play a significant role [4, 9, 25, 52]. Individual differences, such as susceptibility to motion sickness, age, gender, etc., further contribute to the complexity of motion sickness factors [22, 35].

Motion sickness, often assessed using the post-measurement scale SSQ based on discomfort symptoms [47], and its susceptibility, typically measured by the MSSQ based on life experiences [36]. Due to the induction of motion sickness and the further aggravation of motion sickness relying on the continuous accumulation of sensorimotor conflicts caused by sub-locomotion, FMS is designed to assess the dynamic change process in such discomfort feelings caused by sensory conflicts [48], i.e., investigating a one-question scale (i.e., overall level of physiological discomfort) every once in a while. Among them, when the locomotion state changes, some physiological discomfort feelings will significantly increase/decrease in a very short time [6, 67, 93], such as from static to locomotion, from locomotion to static, from translation to rotation, and changes in speed, etc.

These studies inform our experimental configurations of sub-locomotion combinations, factors, and evaluation methods. They also contribute to our result attribution of motion sickness and temporary physiological discomfort.

3 DESIGN CONSIDERATIONS AND PILOT EXPERIMENT

This section enhances the formal experiment's design by introducing considerations for locomotion configurations, including conditions, sub-locomotion types, and influencing factors. It also outlines suitable locomotion parameters based on findings from a pilot experiment.

3.1 Design Considerations

Referring to the single-user locomotion methods in Section 2.1, physical walking is a prevalent method representing continuous embodied locomotion without sensory conflicts [69]. Joystick flying is used in limited physical space, providing continuous locomotion with a driving metaphor, but potential visual-vestibular conflicts may arise [102]. Teleportation is popular for instant position and orientation changes, offering a discrete locomotion method with minimal sensory stimulation for users [33, 73]. In the formal experiment, we choose walking, flying joystick, and teleportation for active users, while passive users engage in basic actions like standing still and looking around (columns 1 and 5 in Table 1, respectively).

Typical walking sub-locomotion includes moving forward, sideways, and turning left/right. Flying joystick's sub-locomotion involves moving forward, sideways, up/down, turning left/right, turning up/down, and rolling left/right. Teleportation sub-locomotion includes position alteration [11] and both position and orientation alteration [96, 99]. These actions are designated as sub-locomotion for active users in the formal experiment (column 2 in Table 1). Typical looking around, involving passive users turning their heads up and down, left and right, is considered sub-locomotion for passive users in the formal experiment's observation (column 6 in Table 1).

Considering the factors affecting sensorimotor conflict outlined in Section 2.3, parameters like locomotion speed, teleportation interval, locomotion time, and MSS are commonly recognized as influential on the locomotion experience [53, 83]. To assess the influence of various combinations of locomotion parameters on experience gaps, based on a pilot experiment, we establish two values (one large and one small) for the speed/teleport-interval of each sub-locomotion as formal experimental parameters. Given the co-locomotion time is consistent for both active and passive users in each sub-locomotion combination and has a clear and easily predictable impact, it is not treated as an independent variable in the formal experiments. Furthermore, exploring the influence of MSS on experience gaps is deemed valuable. Therefore, in the formal experiment, we categorize the combinations of active and passive users into four groups, namely prone to dizziness - not prone to dizziness, not prone to dizziness - prone to dizziness, not prone to dizziness - not prone to dizziness, and prone to dizziness - prone to dizziness.

3.2 Pilot Experiment

The purpose of conducting a pilot experiment was to establish appropriate locomotion parameters for each sub-locomotion in the

Table 1: Locomotion configurations determined for formal experiments based on design considerations and pilot experiment

Active user				Passive user			
Locomotion method	Sub-Locomotion	Optional speed/interval	Determined speed/interval	Superimposed locomotion	Sub-locomotion	Optional speed	Determined speed
walking	walk forward	0.5 m/s & 1 m/s (2) 0.6 m/s & 1.2 m/s (4) 0.7 m/s & 1.4 m/s (2)	0.6 m/s & 1.2 m/s	standing still	static	0	0
	walk sideways	0.3 m/s & 0.6 m/s (3) 0.4 m/s & 0.8 m/s (5) 0.5 m/s & 1 m/s (0)	0.4 m/s & 0.8 m/s				
	turn left/right	20 °/s & 40 °/s (2) 25 °/s & 50 °/s (4) 30 °/s & 60 °/s (2)	25 °/s & 50 °/s				
flying joystick	go forward go left/right go up/down	3 m/s & 6 m/s (6) 4 m/s & 8 m/s (2) 5 m/s& 10 m/s (0)	3 m/s & 6 m/s	look around	turn up & down turn left & right	20 °/s & 40 °/s (1) 25 °/s & 50 °/s (3) 30 °/s & 60 °/s (4)	30 °/s & 60 °/s
	turn left/right turn up/down roll left/right	20 °/s & 40 °/s (2) 25 °/s & 50 °/s (5) 30 °/s & 60 °/s (1)	25 °/s & 50 °/s				
teleportation	alter position alter position & orientation	1 s & 2 s (1) 1.5 s & 3 s (6) 2 s & 4 s (1)	1.5 s & 3 s				

formal experiment, making the experimental setup more closely resemble actual co-locomotion scenarios. Eight participants (4 male, 4 female; mean age = 23.5, SD = 4.04, age range: 18-29) from a local university took part in the pilot experiment. We designed three pairs of optional speeds (3 slow & 3 fast)/teleport-intervals (3 big & 3 small) for each sub-locomotion (columns 3 and 7 in Table 1). Among them, to better measure the impact of the speed/teleport interval on the locomotion gaps, the larger value in the pair was twice larger than the smaller value; these optional values were directly selected or modified slightly from common locomotion parameter settings in some locomotion-related literature, e.g., walk forward speed [7, 70], walk sideways speed [19], turn speed of walking/flying/looking-around [12, 37, 80], translation speed of flying joystick [27, 66], and teleport-interval of teleportation [20]. Participants experienced each optional speed for each sub-locomotion in the formal experimental scene and selected the speed/interval pair they deemed most suitable and preferred for multi-user co-locomotion scenarios. Finally, we tallied participants' choices for each speed/teleport-interval pair (blue values in brackets in Table 1), determining the pair with the most selections as the locomotion parameters for the formal experiment (columns 4 and 8 in Table 1).

4 USER STUDY

This study pairs active and passive users one-on-one to systematically explore experience gaps in diverse locomotion scenarios and assess the influence of various factors.

4.1 Ethics and Participants

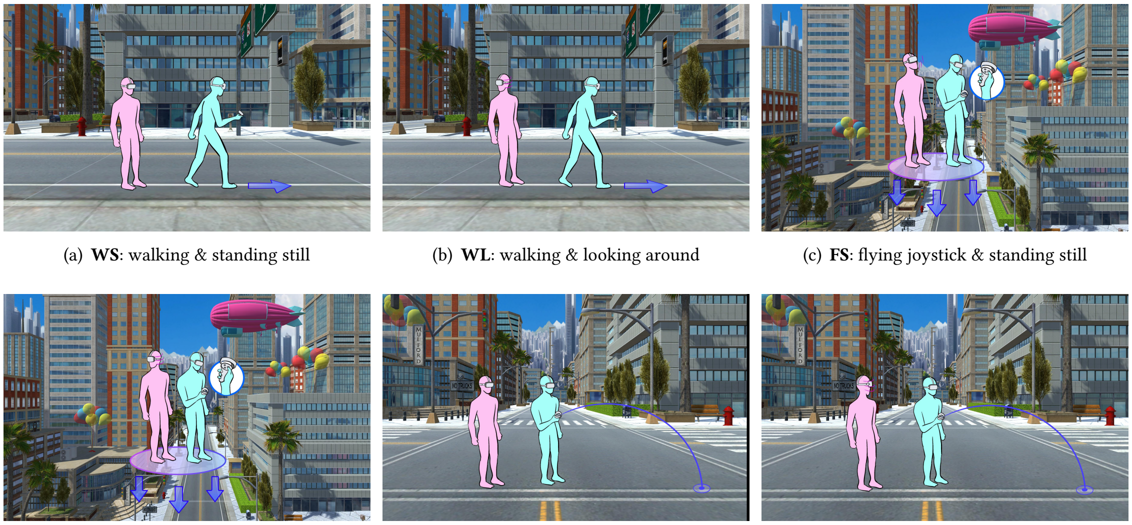
The experiment received ethical approval from a local university and excluded individuals with vestibular disorders or severe motion sickness symptoms. Participants completed the Motion Sickness Susceptibility Questionnaire (MSSQ [36]). According to the classification of MSSQ, participants with a total score >11.3 were classified as prone to dizziness. We recruited 48 students from 4 local universities (25 male and 23 female, mean age = 23.125, median age = 23, SD = 3.26, age range: 18-32). The number of participants with VR experience of proficiency (using VR more than 5 times a week), some proficiency (using VR less than 5 times a week), and none were 14, 18, and 16 respectively. Among them, 24 were active users (12 not prone to dizziness, 12 prone to dizziness), and 24 were passive users (12 not prone to dizziness, 12 prone to dizziness).

To measure the combined effect of active and passive users with different MSS, we paired 24 active users and 24 passive users into 4 combinations: 6 active users of prone to dizziness & 6 passive users of prone to dizziness, 6 active users of not prone to dizziness & 6 passive users of not prone to dizziness, 6 active users of prone to dizziness & 6 passive users of not prone to dizziness, and 6 active users of not prone to dizziness & 6 passive users of prone to dizziness. The rules for paring are as follows: for the first two types of pairs, the difference in MSSQ scores between active and passive users needs to be <5; for the last two types of pairs, the difference in MSSQ scores between active and passive users needs to be >11.3.

4.2 Conditions and Locomotion Nodes

Based on the locomotion methods and superimposed behaviors discussed in Section 3.1, a total of 3*2=6 conditions were designed:

- **WS**: Active user walks, and passive user stands still (Figure 2(a)).
- **WL**: Active user walks, and passive user looks around (Figure 2(b)).
- **FS**: Active user flies by joystick, and passive user stands still (Figure 2 (c)).



(a) **WS**: walking & standing still (b) **WL**: walking & looking around (c) **FS**: flying joystick & standing still

(d) **FL**: flying joystick & looking around (e) **TS**: teleportation & standing still (f) **TL**: teleportation & looking around

Figure 2: The 6 conditions correspond to various combinations of active user's locomotion methods and passive user's behaviors.

- **FL**: Active user flies by joystick, and passive user looks around (Figure 2(d)).
- **TS**: Active user teleports, and passive user stands still (Figure 2(e)).
- **TL**: Active user teleports, and passive user looks around (Figure 2(f)).

As highlighted in Section 2.3, evaluating dynamic changes in feelings during sub-locomotion was essential for comprehending overall experiences and identifying noteworthy locomotion situations. To evaluate temporary experience gaps between active and passive users, we created a set of locomotion nodes for each condition by combining sub-locomotion types and parameters:

- **WS**: 3 types of active user (walk forward, walk sideways, turn left/right) * 2 speeds (0.6 m/s & 1.2 m/s, or 25 °/s & 50 °/s) * 1 type of passive user (standing still) = 6 nodes
- **WL**: 3 types of active user (walk forward, walk sideways, turn left/right) * 2 speeds (0.6 m/s & 1.2 m/s, or 25 °/s & 50 °/s) * 2 types of passive user (head turn up & down, head turn left & right) * 2 speeds (30 °/s & 60 °/s) = 24 nodes
- **FS**: 6 types of active user (go forward, go left/right, go up/down, turn left/right, turn up/down, roll left/right) * 2 speeds (3 m/s & 6 m/s, or 25 °/s & 50 °/s) * 1 type of passive user (standing still) = 12 nodes
- **FL**: 6 types of active user (go forward, go left/right, go up/down, turn left/right, turn up/down, roll left/right) * 2 speeds (3 m/s & 6 m/s, or 25 °/s & 50 °/s) * 2 types of passive user (head turn up & down, head turn left & right) * 2 speeds (30 °/s & 60 °/s) = 48 nodes
- **TS**: 2 types of active user (only alter position, alter position & orientation) * 2 teleport-intervals (1.5 s & 3 s) * 1 type of passive user (standing still) = 4 nodes
- **TL**: 2 types of active user (only alter position, alter position & orientation) * 2 teleport-intervals (1.5 s & 3 s) * 2 types of passive user (head turn up & down, head turn left & right) * 2 speeds (30 °/s & 60 °/s) = 16 nodes

4.3 Experimental Scene, Guiding Objects, and Locomotion Control Methods

We selected an urban scene with abundant reference objects for the experimental environment, as depicted in Figure 3(a). Notably, for **FS** and **FL**, which included vertical translations, we deliberately heightened the city buildings and added mid-air objects like flocks of birds, balloons, and airships to maintain visual locomotion stimulation comparable to ground locomotion.

To assist participants in achieving the required locomotion parameters for walking, teleportation, and head-turning, we employed guiding objects. For walking and looking around, a translucent sphere (0.25m diameter) served as the guiding object, positioned at eye level 2 meters away from participants. The purpose of the translucent setting was to allow the guiding object to be easily seen without blocking the visual stimulation provided by the background behind it. It moved or revolved around participants according to the required direction and speed for the locomotion node (Figure 3(b) and (c)). For teleportation, a 1m diameter disk with a red line segment and countdown was used as the guiding object on the ground (Figure 3(d)). The disk's position indicated the teleportation location, the red line segment denoted the teleportation orientation, and the countdown ensured the required teleportation interval.

For active users, walking involved physical leg movements, such as walking sideways to the left by moving the left leg leftward and bringing the right leg next to it [19]. Participants aimed to follow the speed of guide objects for straight-line walking or body rotations. For flying joystick locomotion, translation/rotation speed parameters were set in the control program. Participants used joysticks and buttons on handles for 3-DoF translations and rotations, with the mapping shown in Figure 4(a) and (b). The translation/rotation

(a) Experimental scene

(b) Active user is following the guiding object to walk forward

(c) Passive user is following the guiding object to turn head left and right

(d) Guiding object for the teleportation position, orientation, and interval

Figure 3: Scene and guiding object of the experiment

direction was constrained to one axis of the global coordinate system, and joystick offset size did not affect speed. Teleportation involved pushing the joystick to project a parabolic ray, with the teleport-target being a blue disc and a red line segment indicating orientation (Figure 4(c)). Handle position and rotation controlled the teleport target, with a transportation range of 0m to 10m. The offset direction of the joystick was mapped to the red line segment of the teleportation target in real-time to control the teleport orientation. Whenever the guide object appeared, the participant needed to align the teleportation target and the guide object before the countdown ended, and released the joystick at the end of the countdown to activate teleportation.

Standing still of passive uesr involved maintaining a motionless state while observing the locomotion of active users. Looking around was a reciprocating action, which required participants to follow the guide objects and first turn their head to one side, and then turn their head in the opposite direction to the other side... until the locomotion node was over. To ensure participant comfort during head-turning, we set inflection points for the guiding object's reciprocating motion based on the typical range of human neck motion[85]: for head-turning up & down, inflection points were at 50° down and 60° up relative to the neutral position; for head-turning left & right, the inflection point was at 70° relative to the neutral position.

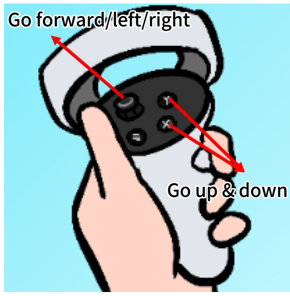
To reduce the influence of body posture, all conditions of the experiment were conducted in the standing position.

4.4 Procedure

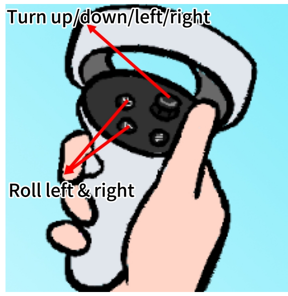
This experiment used repeated measures, i.e., participants were required to complete all locomotion tasks in all conditions. The experimental process was shown in Figure 5.

To balance the number of locomotion nodes across different conditions, we increased the locomotion nodes for each condition to 48, which is the least common multiple for node number of all conditions. The approach involved randomly extracting all locomotion nodes to create Sequence 1 without duplication, then repeating the extraction to form Sequence 2 without duplication and inserting it after Sequence 1, and so on, until the total number of locomotion nodes in Sequence 1 reached 48. Each locomotion node had a duration of 8 seconds.

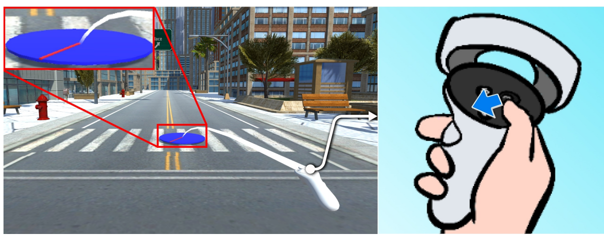
To mitigate the potential impact of multi-user online delays and collaboration issues on the study outcomes, the experiment employed asynchronous separate locomotion to simulate co-locomotion for both active and passive users. The experiment consisted of two stages. In the initial stage, 24 active users completed all locomotion nodes across conditions with a counterbalanced order, and their locomotion data, including condition sequences, node sequences, and trajectories, were recorded. In the second stage, 24 passive users executed the same locomotion nodes in the same order as



(a) Translation control of flying joystick



(b) Rotation control of flying joystick



(c) Position and orientation control of teleportation

Figure 4: Control methods of flying joystick and teleportation

their corresponding active users, and the locomotion trajectories of their paired active users were applied to them. Figure 6(a) illustrates the process of an active user and a passive user consecutively performing a locomotion node (turning left for the active user and looking around up and down for the passive user) in **WL**.

The measurement method of filling out a scale with only one question every once in a while during the experiment has been shown to capture the moment/temporary experience more accurately and was less sensitive to memory deterioration compared to multi-item scales [90, 94]. Such fast single-item scales have been widely used in the evaluation of the temporary experience such as motion sickness [48], presence [10], locomotion sensation [62], etc. Following this methodology, participants rated 5 single-item scales of physiological comfort, psychological comfort, locomotion sensation, presence, and acceptability after completing each locomotion node (Figure 6(b)). The acceptability scale allowed only 0 (unacceptable) or 1 (acceptable) scores, while other scales had a range of 0-10. Except for acceptability, participants provided two scores (pre-locomotion and during-locomotion) for each indicator. We used the difference between the during-locomotion score and before-locomotion score as each indicator score to eliminate the cumulative impact between locomotion nodes.

Once the single-item scale covered the user's view, the participant was reset to the origin of the next locomotion node in preparation for subsequent nodes. In **FS** and **FL**, the origin for nodes involving downward translation was set 50m above the crossroad, while for others, it was 12m above the crossroad center. In other conditions, all origins were at the crossroad center without height. Due to the occlusion of the single-item scales, this reset process was not visible to participants to reduce the potential effects of visual stimulation.

At the onset of each new locomotion node, an arrow appeared in front of the participant, indicating the direction of the upcoming locomotion/head-turning. To simulate actual co-locomotion, the arrow for active users lasted 4s, providing ample preparation, while for passive users, it lasted a random 2s to 6s, introducing unpredictability. The disappearance of the arrow signaled the need for participants to initiate the sub-locomotion corresponding to the node. If the locomotion node featured a guiding object, participants were required to synchronize with its speed or teleport-interval.

After completing all locomotion nodes in each condition, participants exited the VR environment and filled out three post-measurement questionnaires to assess the overall locomotion experience of the condition: SSQ [47] (0-3), Presence Scale [82] (0-10), and a custom questionnaire with three questions on locomotion sensation (0-10), psychological comfort (0-10), and acceptability (0-1, where 0 meant unacceptable and 1 meant acceptable), as outlined in Table 2. Finally, participants underwent interviews to express their feelings regarding locomotion nodes and conditions.

4.5 Measurements of Mitigating bias

To ensure participants' understanding of the experiment, we provided a comprehensive introduction before its commencement. This included details about the experimental process, conditions, overall experience scales, locomotion nodes, and five single-item scales related to temporary experiences. Additionally, we presented demonstration videos showcasing locomotion control methods and addressed participants' questions until they felt familiar with the experiment. Then, clarifications were given for the five single-item scales of measuring temporary experience to participants: physiological comfort referred to the intensity of discomfort in physiological sensations like dizziness, nausea, and eye pain; psychological comfort meant discomfort in psychological feelings such as fear and uneasiness; presence reflected the extent to which participants believed they were in the virtual world; locomotion sensation indicated the extent to which participants perceived themselves in a locomotion state in the view, and acceptability gauged participants' overall feelings about the locomotion node and their willingness to experience it frequently in future co-locomotion. Moreover, for the three post-measurement questionnaires with multiple items, we provided detailed explanations of each item to eliminate ambiguity.

To mitigate the influence of latent and learning effects from repeated measures, we counterbalanced the order in which participants experienced conditions. Between conditions, participants were instructed to rest until any subjective discomfort and fatigue had subsided to reduce the carry-over effects. We verbally confirmed their return to pre-experimental feelings before proceeding to the next condition. Participants received a $40 cash reward, even if they withdrew from the experiment due to discomfort. Four participants discontinued the experiment, and we recruited four replacements with similar MSSQ scores.

4.6 Implementation

The Unity Engine v.2020.3.36f1c1 was used to develop the locomotion control method, pilot experiment, and formal experiments. Active users' locomotion trajectory data were stored as JSON files. Passive users' superimposed views were generated by applying the

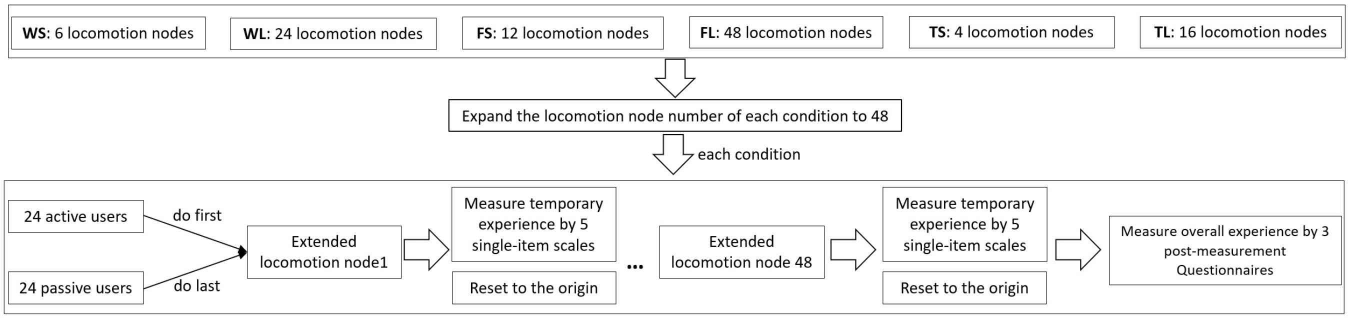
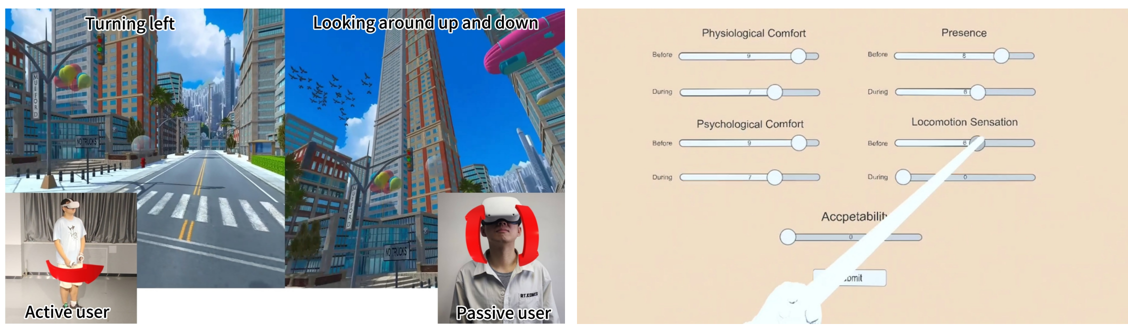


Figure 5: The experimental procedure of user study



(a) Two participants complete a locomotion node in **WL** successively

(b) Filling the 5 single-item scales after each locomotion node

Figure 6: Demonstration of the experimental process

Table 2: The custom post-measurement questionnaire for measuring the overall experience after each condition

No.	Questions
1	What extent do you feel/believe you are always at the locomotion state presented in view at this condition?
2	Do you rarely experience strong fear, uneasiness, and strangeness in this condition?
3	Can you accept the comprehensive feelings of locomotion and be willing to use this condition frequently?

active user’s locomotion trajectory to the parent object of mainCamera. The experiments employed four Oculus Quest 2 headsets [87] and provided a sufficiently large indoor space for active users to walk.

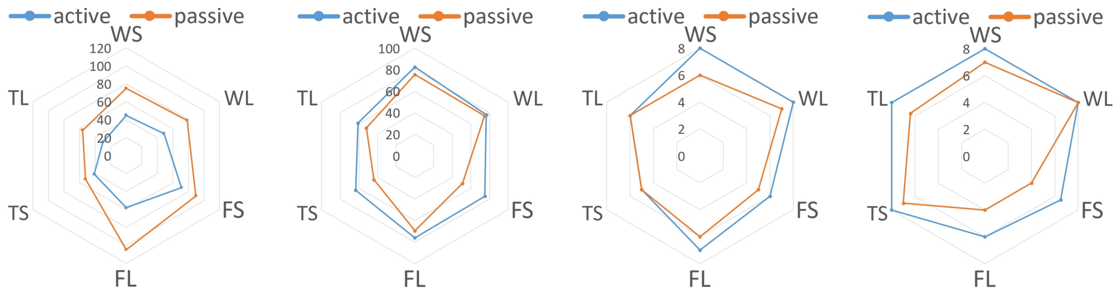
5 RESULTS

In total, we received 48 (participant number) * 6 (condition number) * 48 (locomotion node number) * 5 (single-item scale number) = 69120 temporary experience data of locomotion nodes, and 48 (participant number) *6 (condition number) *3 (questionnaire number) = 864 overall experience data of post-measurement questionnaires.

Since most data did not follow a normal distribution according to a Shapiro-Wilks test, median values were preferred for overall data representation. We employed radar charts to illustrate median value differences between active and passive users in each condition, box plots to depict median values and data distribution of experience gaps, and tables to show median values of experience gaps in each sub-locomotion combination. For condition acceptability, given the binary nature of the data (0 and 1), we used percentage stacked bar charts with the proportion of rated participants. Moreover, we used Wilcoxon signed-rank tests to determine the significant differences between active and passive users in each condition/sub-locomotion combination, and the r value of Wilcoxon to be their effect size [32]. Friedman tests, with post-Friedman pairwise comparisons (Dunn’s approach and Bonferroni correction [26]) in SPSS, assessed significant differences between various conditions on experience gaps, with Kendall’s W test values serving as effect sizes [91]. Bonferroni correction was chosen to reduce family-wise error rate, especially with a relatively large number of conditions [1].

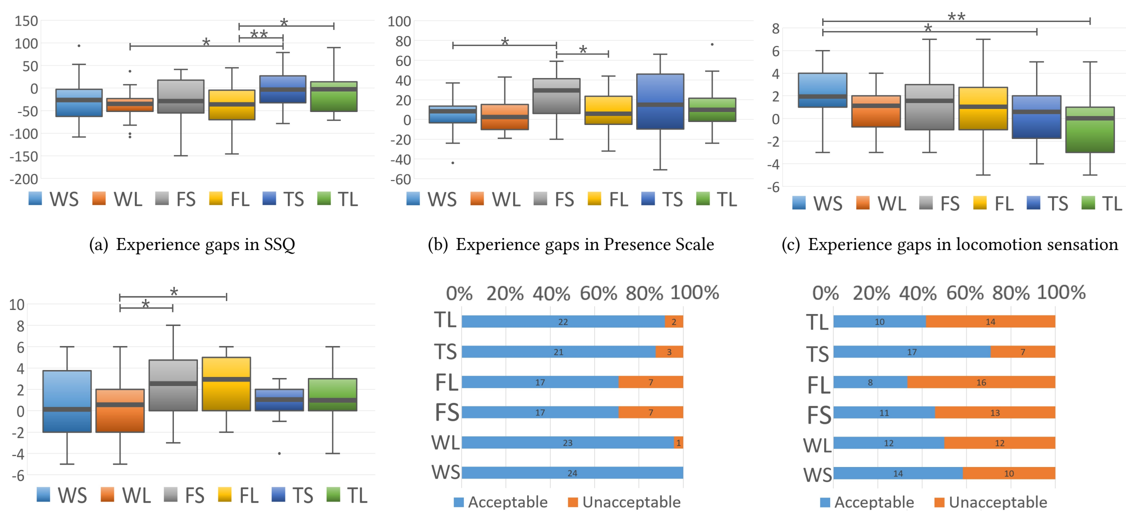
5.1 Experiences of Active and Passive Users in Post-measurement Questionnaires

This section aims to visually represent the experiences of active and passive users in each condition and report significant differences.



(a) The total score of SSQ (b) The total score of Presence Scale (c) Locomotion sensation score (d) Psychological comfort score

Figure 7: The scores of post-measurement questionnaires for the active and passive users in each condition



(a) Experience gaps in SSQ (b) Experience gaps in Presence Scale (c) Experience gaps in locomotion sensation

(d) Experience gaps in psychological comfort (e) Acceptability of active users (f) Acceptability of passive users

Figure 8: The experience gaps between the active and the passive users in post-measurement questionnaires

We computed the total SSQ score using the original paper's method [47] and the total Presence Scale score by summing all item scores. Median values for total SSQ score, total Presence Scale score, and scores for locomotion sensation and psychological comfort in the Custom Questionnaire were illustrated using four radar charts (Figure 7).

The results of Wilcoxon signed-rank tests showed that in the total score of SSQ, there were significant differences between active and passive users in **WS** ($Z = 2.388$, $p = .017$, $r = .345$), **WL** ($Z = 3.846$, $p < .001$, $r = .555$), **FS** ($Z = 2.186$, $p = .029$, $r = .315$), and **FL** ($Z = 3.514$, $p < .001$, $r = .507$); in the total score of Presence Scale, there were significant differences between active and passive users in **FS** ($Z = -3.688$, $p < .001$, $r = -.532$), **TS** ($Z = -2.1$, $p = .036$, $r = -.303$), and **TL** ($Z = -2.401$, $p = .016$, $r = -.346$); in the score of locomotion sensation, there were significant differences between active and passive users in **WS** ($Z = -3.509$, $p < .001$, $r = -.506$) and **FS** ($Z = -2.988$, $p = .003$, $r = -.431$); in the score of psychological comfort, there were significant differences between active and passive users in **FS** ($Z = -3.385$, $p = .001$, $r = -.488$), **FL** ($Z = -3.459$, $p = .001$, $r = -.499$), and **TL** ($Z = -2.371$, $p = .018$, $r = -.342$).

Overall, in all conditions, there were significant differences in at least one experience indicator. **FS** exhibited significant differences between active and passive users across all experience indicators, while **TS** showed a significant difference only in presence.

5.2 Experience Gap of Various Conditions in Post-measurement Questionnaires

This section visually presents experience gaps, and their data distributions in each condition, and compares significant differences between conditions. The results serve as a reference to identify conditions requiring further analysis and improvement due to more pronounced gap problems, as well as conditions with smaller gaps suitable for direct use in co-locomotion scenes. Experience gap values were calculated as the active user's questionnaire score minus the passive user's score, utilized in box plots and significance analysis.

Table 3: The temporary experience gaps of various sub-locomotion combinations. In the table, *Sig.* indicates significant differences; purple denotes sub-locomotion combinations with rare negative gaps; green/yellow indicates sub-locomotion combinations with substantial gaps in some indicators where the rotation axes of active and passive users differ/are the same; blue/red denotes cases where active users find it acceptable but passive users do not or where both find it unacceptable.

Condition	Sub-locomotion combinations		Physiological Comfort		Psychological Comfort		Presence		Locomotion Sensation		Acceptability percentage	
	active	passive	Sig.	Gap	Sig.	Gap	Sig.	Gap	Sig.	Gap	active	passive
WS	go forward	standing still	**	1	/	0	/	0	***	2	99%	72%
	go left/right	standing still	/	1	/	0	/	0	*	1	86%	63%
	turn left/right	standing still	***	2	/	1	/	0	**	2	92%	48%
WL	go forward	head turn up & down	/	0	/	1	/	-1	**	-2	98%	80%
	go left/right	head turn up & down	*	1	/	1	/	1	/	0	88%	66%
	turn left/right	head turn up & down	***	4	**	1	**	1	/	1	94%	45%
	go forward	head turn left & right	*	1	/	0	/	0	*	1	99%	81%
	go left/right	head turn left & right	**	1	/	1	/	0	/	-1	89%	77%
	turn left/right	head turn left & right	**	3	***	3	**	2	***	3	93%	34%
FS	go forward	standing still	*	1	/	1	**	2	*	1	86%	62%
	go left/right	standing still	/	0	*	2	*	1	/	0	82%	63%
	go up/down	standing still	/	1	**	1	/	1	*	1	80%	57%
	turn up/down	standing still	**	2	**	2	*	1	*	1	78%	53%
	turn left/right	standing still	*	2	/	1	*	2	**	2	74%	59%
	roll left/right	standing still	***	3	***	2	***	2	**	2	43%	38%
FL	go forward	head turn up & down	*	1	*	1	**	-2	*	-1	85%	69%
	go left/right	head turn up & down	/	0	**	2	*	1	/	1	81%	58%
	go up/down	head turn up & down	*	1	***	3	*	-1	*	-1	84%	45%
	turn up/down	head turn up & down	***	3	**	2	**	2	***	3	84%	43%
	turn left/right	head turn up & down	***	2	/	1	**	1	/	1	77%	42%
	roll left/right	head turn up & down	***	3	***	3	*	1	/	0	49%	28%
	go forward	head turn left & right	/	1	/	1	/	1	/	1	83%	65%
	go left/right	head turn left & right	*	2	/	1	/	0	*	-2	82%	70%
	go up/down	head turn left & right	/	1	***	3	/	0	/	1	79%	59%
	turn up/down	head turn left & right	***	2	***	3	*	1	*	2	83%	36%
	turn left/right	head turn left & right	**	2	/	0	***	3	***	3	81%	29%
	roll left/right	head turn left & right	***	4	***	3	*	2	*	2	47%	35%
TS	alter pos	standing still	/	0	/	0	***	2	/	0	92%	78%
	alter pos & ori	standing still	/	0	/	0	***	3	/	1	90%	72%
TL	alter pos	head turn up & down	*	-1	/	0	/	1	*	-1	93%	64%
	alter pos & ori	head turn up & down	/	0	**	1	**	2	/	-1	88%	44%
	alter pos	head turn left & right	/	1	**	2	*	2	/	-1	90%	46%
	alter pos & ori	head turn left & right	*	1	**	2	**	2	/	1	89%	41%

The results of Friedman test showed that the score of SSQ ($\chi^2(5) = 20.145$, $p = .001$, $W = .336$), Presence Scale ($\chi^2(5) = 14.025$, $p = .015$, $W = .234$), locomotion sensation ($\chi^2(5) = 17.287$, $p = .004$, $W = .288$), and psychological comfort ($\chi^2(5) = 18.258$, $p = .003$, $W = .304$) were significantly affected by conditions. The boxplots of the experience gap data and the significant differences between conditions by Pairwise Comparisons were shown in Figure 8(a)-(d), which * represented $p < .05$, ** represented $p < .01$ and *** represented $p < .001$.

Moreover, the results of the active and passive users' acceptability results were displayed in the percent stacked bar chart (Figure 8(e) and (f)). According to the acceptable ratio of the active users minus the acceptable ratio of the passive users, the acceptability gaps of **WS**, **WL**, **FS**, **FL**, **TS** and **TL** were 50%, 29.1%, 37.5%, 25%, 45.8%, 41.7% respectively.

Overall, **FL** exhibited the greatest gap in motion sickness and psychological comfort, **FS** showed the largest presence gap, and **WS** had the most substantial locomotion sensation gap. Regarding acceptability, most active users in all conditions found the locomotion acceptable, but over half of the passive users could not accept in **WL**, **FS**, **FL**, and **TL**.

5.3 Temporary Experience Gaps in Various Sub-locomotion Combinations

This section aims to intuitively represent the temporary experience gaps between active and passive users for each sub-locomotion combination in each condition. On the one hand, this could help researchers understand the performances of various sub-locomotion combinations and the impact differences of various sensory conflict types; on the other hand, this provided a reference for this paper to analyze the reasons for the overall experience gaps of condition, and to screen out sub-locomotion combinations with large experience gaps that deserve attention/avoidance/intervention.

First, we categorized locomotion nodes into various sub-locomotion combinations based on the formal of active and passive users (refer to Table 3). Then, we computed the temporary experience score for each active and passive user by subtracting the before-locomotion score from the during-locomotion score. The temporary experience gap score was obtained by subtracting the passive user's temporary experience score from that of the active user. The table includes significance results (*Sig.*) from Wilcoxon tests and median values of temporary experience gaps (*Gap*). Additionally, the last two columns indicate the acceptable percentage for each sub-locomotion combination among active and passive users.

Overall, in terms of temporary experience gaps in psychological and physiological comfort, numerous sub-locomotion combinations in **FL** exhibited significant differences for both active and passive users. Turning actions by active users generally led to substantial experience gaps in various indicators. Notably, when the active users turn and the passive users turn their heads in **WL** and **FL**, whether the rotation axes were the same (yellow backgrounds) or different (green backgrounds), most indicators displayed significant gaps, with over half of passive users unable to accept them. Interestingly, when active users translated while passive users turned their heads in a similar direction, this mitigated the gaps in presence and locomotion sensation, and even resulted in negative experience gap values for some sub-locomotion combinations (purple backgrounds).

5.4 Acceptability of Conditions and Sub-Locomotion Combinations

This section aimed to screen out some conditions and sub-locomotion combinations based on acceptability results: those acceptable to both active and passive users, those unacceptable to both, and those acceptable to active users but not to passive users. No cases were found where a condition was unacceptable to active users but acceptable to passive users. Filtering rules were as follows: if both active and passive users had acceptability above 50%, it was considered acceptable to both; if both had acceptability below 50%, it was deemed unacceptable to both; when the active user's acceptability exceeded 50% while the passive user's was below 50%, and their acceptability difference exceeded 25%, it was categorized as acceptable for the active user but unacceptable for the passive user.

According to Figure 8(e) and (f), conditions acceptable to both active and passive users were **WS**, **WL**, and **TS**; those acceptable to active users but unacceptable to passive users include **FS**, **FL**, and **TL**. For sub-locomotion combinations, we marked unacceptable to both active and passive users (red backgrounds), acceptable to active users but not to passive users (blue backgrounds) in Table 3, and unmarked acceptability meant both users could accept it.

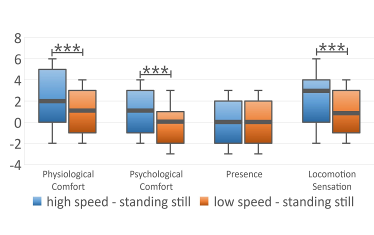
5.5 Temporary Experience Gap of Various Speed or Teleport-interval Combinations

This section aimed to assess the impact of different combinations of locomotion speeds/teleport-intervals on temporary experience gaps and identify significant differences between these combinations. We classified the locomotion nodes into 6 types of combinations: high speed/small interval - standing still, low speed/large interval - standing still in **WS**, **FS**, and **TS**; high speed/small interval - high turning head speed, high speed/small interval - low turning head speed, low speed/large interval - high turning head speed, low speed/large interval - low turning head speed in **WL**, **FL**, and **TL**.

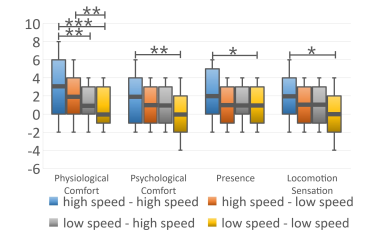
We used the same calculating method of the temporary experience gap score in Section 5.3. The results of Wilcoxon signed-rank tests showed that in **WS**, there were significant differences between high speed-standing still and low speed - standing still in physiological comfort ($Z = -13.292$, $p < .001$, $r = -.392$), psychological comfort ($Z = -10.376$, $p < .001$, $r = -.306$), and locomotion sensation ($Z = -13.583$, $p < .001$, $r = -.400$); in **FS**, there were significant differences between high speed-standing still and low speed - standing still in physiological comfort ($Z = -13.508$, $p < .001$, $r = -.398$), psychological comfort ($Z = -12.210$, $p < .001$, $r = -.359$), presence ($Z = -9.531$, $p < .001$, $r = -.281$), and locomotion sensation ($Z = -9.459$, $p < .001$, $r = -.279$); in **TS**, there were significant differences between high speed-standing still and low speed - standing still in presence ($Z = -11.626$, $p < .001$, $r = -.343$), and locomotion sensation ($Z = -10.732$, $p < .001$, $r = -.316$). The results of Friedman tests showed that in **WL**, there were significant differences between 4 walking speed-head turning speed combinations in physiological comfort ($\chi^2(3) = 30.016$, $p < .001$, $W = .532$), psychological comfort ($\chi^2(3) = 22.086$, $p < .001$, $W = .451$), presence ($\chi^2(3) = 16.315$, $p = .003$, $W = .325$) and locomotion sensation ($\chi^2(3) = 26.076$, $p < .001$, $W = .463$); in **FL**, there were significant differences between 4 flying speed-head turning speed combinations in physiological comfort ($\chi^2(3) = 42.384$, $p < .001$, $W = .478$), psychological comfort ($\chi^2(3) = 14.352$, $p = .004$, $W = .301$), presence ($\chi^2(3) = 9.854$, $p = .011$, $W = .309$) and locomotion sensation ($\chi^2(3) = 9.781$, $p = .012$, $W = .354$); in **TL**, there were significant differences between 4 teleport interval-head turning speed combinations in physiological comfort ($\chi^2(3) = 9.994$, $p = .010$, $W = .469$), psychological comfort ($\chi^2(3) = 9.979$, $p = .011$, $W = .464$), presence ($\chi^2(3) = 10.354$, $p = .010$, $W = .522$) and locomotion sensation ($\chi^2(3) = 8.978$, $p = .022$, $W = .365$).

The boxplots of the temporary experience gap data and the significant differences between various speed/interval-turning head speed combinations by Pairwise Comparisons were shown in Figure 9(a)-(f), which * represented $p < .05$, ** represented $p < .01$ and *** represented $p < .001$.

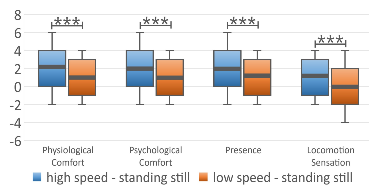
Overall, high speed/low interval-standing still had the largest temporary experience gaps in **WS**,**FS**, and **TS**; high speed/low interval-high turning head speed generally had the largest temporary experience gap, followed by high speed/low interval-low turning head speed in **WL**,**FL**, and **TL**.



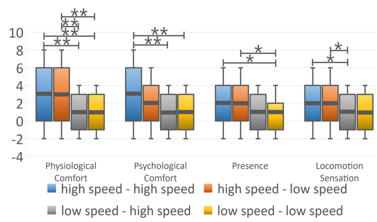
(a) Experience gap of speed combinations in **WS**



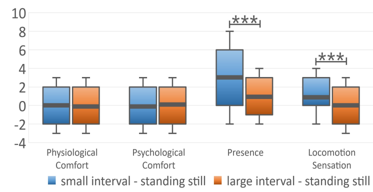
(b) Experience gap of speed combinations in **WL**



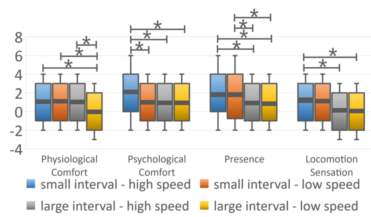
(c) Experience gap of speed combinations in **FS**



(d) Experience gap of speed combinations in **FL**

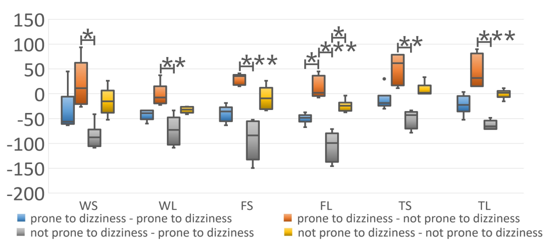


(e) Experience gap of interval combinations in **TS**

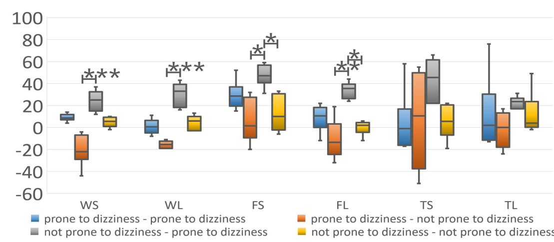


(f) Experience gap of interval combinations in **TL**

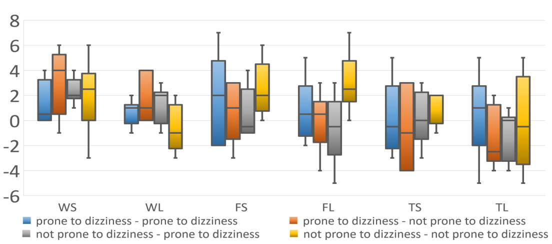
Figure 9: Temporary experience gap between active and passive users of various speed/teleport-interval combinations



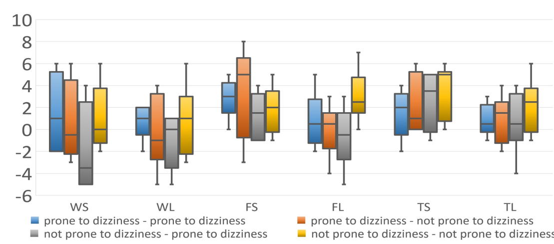
(a) Experience gap of motion sickness susceptibility combinations in SSQ



(b) Experience gap of MSS combinations in Presence Scale



(c) Experience gap of MSS combinations in locomotion sensation



(d) Experience gap of MSS combinations in psychological comfort

Figure 10: Experience gaps of various motion sickness susceptibility combinations in post-measurement questionnaires

5.6 Experience Gap of Various MSS Combinations

According to the 4 combinations of MSS in Section 4.1, this section aimed to investigate the impact of MSS combinations on experience gaps, and significant differences between various MSS combinations. On the one hand, it was worth exploring whether MSS had impacts on the experience gaps of indicators besides the easily predictable SSQ. On the other hand, although not prone to dizziness - prone to dizziness may be easily predictable to cause the largest motion sickness gap, it was interesting to know the gap ranking of other MSS combinations.

The calculating method of experience gap values was the same as in Section 5.2. The Friedman test results showed that for SSQ, there were significant differences between MSS combinations in **WS** ($\chi^2(3)$ = 9.000, p = *.029*, W = .500), **WL** ($\chi^2(3)$ = 13.881, p = *.003*, W = .671), **FS** ($\chi^2(3)$ = 17.746, p < *.001*, W = .593), **FL** ($\chi^2(3)$ = 17.983, p < *.001*, W = .600), **TS** ($\chi^2(3)$ = 15.001, p = *.002*, W = .533), and **TL** ($\chi^2(3)$ = 17.746, p < *.001*, W = .686); for Presence Scale, there were significant differences between MSS combinations in **WS** ($\chi^2(3) = 17.586$, $p < .001$, $W = .677$), **WL** ($\chi^2(3) = 17.024$, $p = .001$, $W = .544$), **FS** ($\chi^2(3) = 11.800$, $p = .008$, $W = .656$), and **FL** ($\chi^2(3) = 14.005$, $p = .003$, $W = .778$).

The boxplots of the experience gap data and the significant differences between various MSS combinations by Pairwise Comparisons were shown in Figure 10(a)-(d), which * represented $p < .05$, ** represented $p < .01$, and *** represented $p < .001$.

Overall, not prone to dizziness- prone to dizziness had the largest experience gap in SSQ and Presence Scale, followed by prone to dizziness - prone to dizziness, and prone to dizziness - not prone to dizziness had the smallest experience gap. Interestingly, MSS combinations had no significant impact on locomotion sensation and psychological comfort.

6 DISCUSSION

This study is exploratory, lacking pre-formulated hypotheses before the experiment. Therefore, all discussions in this section present exploratory insights [106].

6.1 The Impact of Conditions on the Experience Gap in Post-measurement Questionnaires

In **WS** and **WL**, active users experience natural locomotion sensations with minimal sensorimotor conflict, due to aligning visual, vestibular, and proprioceptive stimulation during walking. In **WS**, passive users only receive visual stimulation, while in **WL**, looking around of passive users further causes mismatched perceptions of locomotion directions in vision and other senses. This results in significant motion sickness differences between active and passive users in these conditions. Surprisingly, these sensory conflicts don't lead to a significant difference in presence between active and passive users in **WS** and **WL**. Because participant feedback suggests that the views with left/right shaking and slight jittering caused by active users' alternating steps contribute to the walking illusion for passive users, making them feel like they are walking. This effect is more pronounced in **WL**, eliminating the significant difference in locomotion sensation between active and passive users.

The **FS** aligns with the setup and some results of Stoffregen's driving-based co-locomotion research [16, 21], active and passive users differ only in locomotion intention and weak proprioceptive stimulation (i.e., pushing joystick) in such condition, thus confirming the "driver-passenger effect" and highlighting the key role of locomotion intention again. Differently, our study introduces a higher degree of freedom in locomotion, with more axes moving and rotating in locomotion nodes, especially in **FL**, where passive users also turn their heads. This adds depth to the results and provides additional insights not explored in their research. The prevalence of turning-related locomotion nodes contributes to **FS** and **FL** exhibiting significant differences in many indicators compared to other conditions. The changes in flying height, especially in **FL**, may induce psychological discomfort for passive users lacking locomotion control, resulting in feelings of fear and excitement. In **FL**, participants reported sensations akin to viewing surrounding scenery on a roller coaster, leading to both excitement and dizziness. On the contrary, few active users report this feeling, and much of their feedback is that controlling flight is fun. This likely explains the significant gaps in physiological and psychological comfort in **FS** and **FL**, with no significant gaps in presence and locomotion sensation between active and passive users in **FL**.

Active users in **TS** and **TL** said that they can better grasp the timing of transmission based on the guiding object, and such locomotion hardly causes dizziness. Passive participants in **TS** reported that they felt as though they were viewing PPTs or dynamic picture collections which is strange, diminishing their presence. In **TL**, many passive participants reported that they were disgusted with such locomotion due to sudden teleportation during observing scenes hindered obtaining desired scene information, leading to reduced spatial perception and a sense of getting lost. This results in significant differences between active and passive users in presence and psychological comfort in **TL**, along with a large acceptability gap between **TL** and **TS**.

6.2 The Impact of Sub-locomotion Types on the Temporary Experience Gap

Significant differences in temporary locomotion experiences exist between active and passive users, particularly during active user turns. In **WL** and **FL**, when the active user's rotation axis aligns with the passive user's head-turning axis, very large experience gaps emerge (e.g., yellow parts in Table 3). This is due to passive users visually perceiving doubled or mutually canceling speeds depending on the same or reverse of active and passive users' turning directions, similar to applying dynamic visual redirection with rotation gain, i.e., changing the mapping of physical actions to corresponding virtual responses [42, 71], results in sudden visual speed changes when head-turning direction changes as reported by participants. Additionally, significant experience gaps occur when active and passive users rotate at different axes (i.e., green backgrounds in Table 3). We speculate that this is due to passive users visually perceiving compound rotation of two rotation axes, conflicting with the vestibular sense perceiving rotation along only one axis, leading to sensorimotor conflict and potential pseudo-Coriolis effects that intensify motion sickness [23, 49, 50].

Furthermore, at certain locomotion nodes where the active user translates and the passive user turns head in a similar direction (e.g., purple parts in Table 3), there are small gaps in presence and locomotion sensation between active and passive users. Some passive user scores even surpass those of active users, with reports of strong locomotion sensations like they are really moving despite merely rotating their heads. This phenomenon may be attributed to the head-turning action involving a head revolution around the neck (i.e., in addition to rotation, there is also arc-shaped translation), especially the action of looking around up and down; when active users translate and passive users turn heads in similar directions (e.g., translating forward/up/down of active users and turning the head up and down of passive users) can confuse the passive user's brain to mistakenly regard these visual and vestibular signals as aligned and create a translation illusion. This characteristic is leveraged in some embodied locomotion methods in VR like head joystick [41], body tilts [31, 41, 104], which control translation by head or torso rotation/tilting, proving effective in producing excellent locomotion sensation.

Additionally, in **FS** and **FL**, the active users' roll rotations significantly impact their and passive users' physiological discomfort.

This could be attributed to the infrequency of rolling rotation in daily life; The up/down translation by the active user also affects the gaps in psychological comfort. Some passive users reported feeling startled or uneasy, especially during sudden rises or falls. In **TS** and **TL**, teleportation disrupts the passive user's continuous observation, resulting in a substantial difference in psychological comfort and presence; the locomotion sensation from discrete teleportation in active users is not as strong as the locomotion sensation induced by passive users' head-turning, leading to some negative gaps in the locomotion sensation.

6.3 The Impact of Speed/Teleport-interval and MSS on the Experience Gap

In general, the impact of locomotion/head-turning speed and teleport-interval on many temporary experience gaps is obvious. It is easy to understand the gaps of high speed/small interval - standing still is bigger than high speed/small interval - standing still in **WS**, **FS**, and **TS**, due to stronger visual stimulation can further increase the sensory conflict level, especially for passive users without locomotion intention, vestibular and proprioceptive stimulation. On the other hand, high speed/small interval - high turning head speed and low speed/high interval - low turning head speed respectively produce the biggest and smallest experience gaps in **WL**, **FL**, and **TL**, this is also straightforward to comprehend, due to the passive users looks around more easily further exacerbating the sensorimotor conflict than when standing still. Interestingly, high speed/small interval - low turning head speed usually has greater experience gaps in some indicators than low speed/big interval - high turning head speed, which suggests that in co-locomotion, the locomotion parameters of the active user play a more important role in the experience gap than the locomotion parameters of the passive user.

Moreover, as a factor known to significantly affect motion sickness levels, MSS not only has a significant impact on motion sickness gaps, but also has a significant impact on presence gaps, this shows that the intensity of motion sickness also affects the presence gap. Among them, not prone to dizziness - prone to dizziness usually has the largest experience gaps, which is easy to understand. Interestingly, for the other 3 MSS combinations, prone to dizziness - not prone to dizziness usually has the smallest experience gaps, and prone to dizziness - prone to dizziness and not prone to dizziness - not prone to dizziness have no significant difference. These ranking results provide references for the pairing/combinations of active and passive users in actual co-locomotion situations. Moreover, the absence of an impact on locomotion sensation and psychological comfort from MSS suggests that the significant gap of motion sickness alone is insufficient to cause the experience gaps in such two indicators for co-locomotion scenarios.

6.4 Research Values and Inspirations

The chosen conditions and sub-locomotion combinations in this study are representative, covering three categories of sensory-aligned embodied locomotion methods (walking), locomotion methods with driving metaphor and proprioceptive stimuli (flying joystick), and discrete locomotion (teleportation), and two types of common interactive behaviors of passive users. Importantly, beyond locomotion intent, the study focuses on experience gaps caused by sensorimotor conflicts, prevalent in co-locomotion scenarios. It can be reasonably expected that the results of this paper can be applied to more actual co-locomotion scenarios with collaborative tasks. For some dynamic co-locomotion scenarios, such as in intense multiplayer games where the active user drives a car to evade enemy pursuit while the passive user is responsible for attacking enemies, it is difficult for the active and passive users to communicate locomotion intent, which is similar to the setup in this paper, so the results of this paper can directly provide reference to ensure the experience. For scenarios allowing locomotion intent communication, such as the active user leads the way while the passive user performs tasks, the study's results on conditions/sub-locomotion combinations related to sensorimotor conflicts (e.g., co-locomotion involving passive users looking around) are also valuable references.

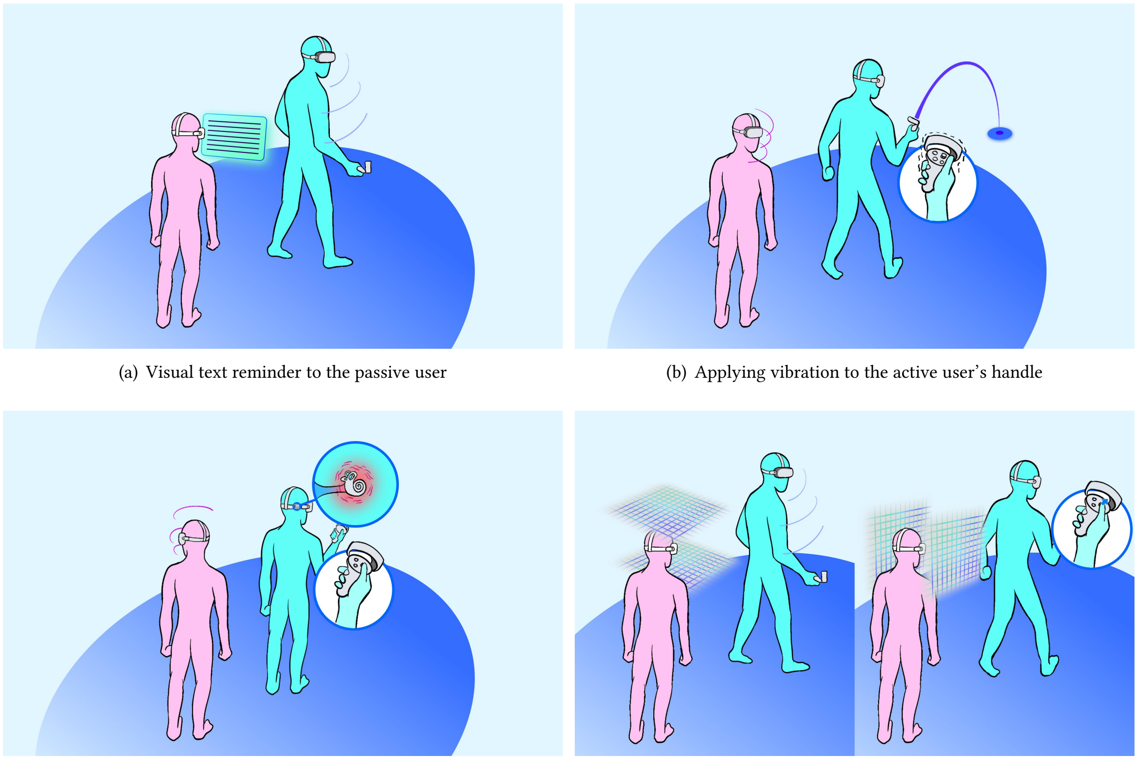
Specifically, Exploring the experience gaps between active and passive users in VR co-locomotion offers several research values and inspirations, including:

Firstly, based on the gaps in acceptability and other experiential indicators for each condition and between conditions (Sections 5.1 and 5.2), designers can gain an understanding of the strengths and weaknesses of each co-locomotion condition and the rankings of conditions. This insight helps identify which conditions offer better experiences and can be directly applied in co-locomotion scenarios and which ones require further improvement for effective application.

Secondly, as an aspect of experience rarely explored in other studies, the accumulation of temporary experiences will lay the groundwork for the overall experience of the entire locomotion condition. Designing various sub-locomotion combinations allows for a detailed understanding of which combinations may result in significant temporary experience gaps (Section 5.3). This understanding enables designers to intentionally avoid or intervene in these sub-locomotion combinations when designing co-locomotion scenarios, e.g., setting up landscapes or generating dynamic elements such as pedestrians, animals, etc., to attract the attention of either active or passive users, thereby reducing user behaviors that lead to significant experience gaps. Simultaneously, it helps identify combinations that can be confidently utilized in such scenarios.

Thirdly, the evaluation results of motion parameter combinations can serve as a basis for setting the speed/teleportation interval in co-locomotion scenarios. For instance, prioritizing the rational adjustment of parameters for the active user, who plays a dominant role in the experience gap. The evaluation results of MSS combinations can guide the pairing of active and passive users. For example, prioritizing the users who are prone to dizziness as active users and the users who are not prone to dizziness as passive users can help minimize the experience gap. In this context, although the active user may be more susceptible to dizziness, they have control over the motion and can adjust it at any time to mitigate their physiological discomfort.

Fourth, this study's speculation on numerous causes of experience gaps contributes to a deeper understanding of how the human perceptual system responds to various co-locomotion scenarios. It also contributes to unveiling the complex relationship between sensory stimuli and user experience in virtual co-locomotion environments.



(a) Visual text reminder to the passive user

(b) Applying vibration to the active user's handle

(c) Applying passive user's vestibular feelings to active user through GVS

(d) Applying visual barriers to passive users to limit look around

Figure 11: Dynamic intervention methods based on temporary experience gaps in sub-locomotion combinations

Finally, most participants' feedback indicates that the primary determinant of the acceptability of a condition or sub-locomotion is physiological comfort, followed by psychological comfort, then presence, and finally, locomotion sensation. Therefore, we suggest prioritizing the acceptability gap when designing co-locomotion scenarios, as it provides a comprehensive feeling of the condition/locomotion node experience. Subsequently, consider the physiological comfort gap, psychological comfort gap, presence gap, and locomotion sensation gap in that order. This provides valuable guidance for developers working on applications involving co-locomotion, helping them address challenges and create more inclusive and satisfying virtual reality applications.

6.5 Limitations and Future Work

Despite our study implementing a balanced condition sequence and providing a relatively ample rest time between conditions, like many other within-subject designs, may still be unable to completely eliminate the carry-over effects of motion sickness. Some preliminary research suggests that motion sickness may sometimes exhibit a delayed onset, with participants feeling fine at one time but later experiencing worsened symptoms [103]. Considering the current lack of scientific evidence demonstrating the potential long-term nature of motion sickness and its impact on the development of carry-over effects (e.g., linearly or not), these unclear effects may to some extent constrain the reliability of the motion sickness results discussed in this paper. In the future, we will further screen out conditions and locomotion nodes that are noteworthy or interesting from our findings, and adopt more reliable methods to eliminate carry-over effects between conditions, such as allowing intervals of more than 24 hours between different conditions, to further validate our results and the potential reasons for our speculations.

To measure temporary experiences, we set locomotion nodes by combining possible sub-locomotion and speed/interval parameters for each condition. Although we balance the settings of locomotion nodes for each condition in terms of quantity, duration, and sequence to simulate actual co-locomotion scenarios as closely as possible, there may still be some impact on the comparability between conditions.

Similar to the experimental strategy of Stoffregen's works [15, 16, 21], our study evaluates active and passive users in isolation to simulate co-locomotion while minimizing collaborative interaction between them. This approach may to some extent impact the generalizability of the results. In the future, we will further research the experiential gaps of co-locomotion scenarios with collaborative tasks and communicative intentions.

In the future, we will further explore feasible automated sensory intervention methods based on the results of this paper in co-locomotion scenarios. For example, when the active user turns body, the application system automatically provides a visual text reminder to the passive user to avoid looking around (Figure 11(a)); when the passive user looks around, the application system applies vibration to the active user's handle to prevent the active user's teleportation (Figure 11(b)); applying dynamic galvanic vestibular stimulation (GVS) to the active user to make the vestibular sensation of the active user similar to that of the passive user, so that the active user can adjust locomotion behavior more timely, such as locomotion speed, speed change frequency, and rest time (Figure 11(c)); when the active user rotates, visual barriers will be generated on the upper and lower sides or the left and right sides of the passive user's head, so that the passive user cannot see the surrounding environment even if he/she turns head, prompting he/she to cancel the turning head intention (Figure 11(d)). The strength of these intervention methods can based on the magnitude of the temporary experience gap results of sub-locomotion combinations in this paper.

7 CONCLUSION

In conclusion, our study delved into the experience gaps beetween the active and passive users in multi-user co-locomotion, particularly focusing on temporary experience gaps of sub-locomotion combinations. Through a comprehensive examination of various combinations of active user's locomotion methods, passive user's behaviors, sub-locomotions, speed/interval, and MSS, we identified significant experience gaps within conditions and sub-locomotion combinations, shedding light on noteworthy situations that influence user experience. Overall, passive users tended to experience more pronounced discomfort compared to active users, especially in conditions involving passive users looking around. Intriguingly, sensory conflict gaps were notably accentuated during sub-locomotion combinations where active users turned while passive users observed their surroundings; instances where active user translation and passive user head rotation were aligned resulted in heightened presence and locomotion sensation for the passive user, suggesting complex human coping mechanisms for sensorimotor conflicts. These findings underscore the importance of considering locomotion conditions, sub-locomotion types and parameters, and individual differences to enhance the co-locomotion experience. Finally, our analysis encompassed the potential causes, values, and inspirations of study results, revealing nuanced insights into the co-locomotion.

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