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.

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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探索主动用户与被动用户之间的体验差距 在虚拟现实中的多用户移动期间

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(a) 多用户驾驶 (b) 群体导航 (c) 经验分享

图1: 多用户协同移动的典型虚拟现实场景，其中主动与被动用户具有不同的移动体验。

摘要

虚拟现实中的多用户移动已变得越来越普遍，同时也带来了诸多挑战。导致这些挑战的一个关键因素在于协同移动过程中主动与被动用户之间的体验差距。然而，对于这些体验差距如何在多样化的多用户共同运动场景中体现及其程度，目前仍缺乏深入理解。本文系统地探讨了生理与心理体验指标上的差距。

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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

这些指标涉及不同移动情境下的主动用户与被动用户，例如当主动用户行走、操纵杆飞行或瞬移时，被动用户静止站立或环顾四周的场景。

我们还评估了子移动类型等因素的影响，
速度/瞬移间隔、晕动症易感性等。据此，我们揭示了主动与被动用户之间的可接受性差异，并提出如何利用显著的实验发现来通过规避或干预缓解协同移动过程中的不适感。

CCS概念

• **人本计算 → 虚拟现实；用户研究** .

关键词

多用户虚拟现实, 移动体验, 经验差距, 感官
冲突

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天仁 Luo、枫林 Lu、吕家福、谭晓辉、刘畅、颜芳志、黄瑾、余春、韩腾和田峰。2024。探索VR中多用户移动时主动与被动用户的体验差距。发表于计算机系统中的人为因素CHI会议（CHI 2024），2024年5月11日至16日，美国夏威夷州檀香山。美国计算机协会，美国纽约州纽约市，19页。https://doi.org/10.1145/3613904.3641975

1 引言

随着虚拟现实设备和应用的日益普及,
近年来，沉浸式环境中的多用户活动与体验受到了广泛关注。虚拟现实中的协同移动作为一种关键的多用户交互形式，指的是用户在虚拟环境中以群体方式进行移动或导航，其中一种典型模式是由一名用户主导应用操作（称为主动用户），其余用户则作为乘客（称为被动用户）。这种模式在多人游戏、团队体验、训练模拟和虚拟会议等场景中尤为常见，参与者可通过群体移动共同探索虚拟世界、集结至特定区域、练习团队协作、协调行动，并以更具动态性和沉浸感的方式互动。具体场景示例包括：在多人开放世界游戏中载送队友（图1(a)）、VR旅游时担任导游[99, 100]（图1(b)）、以及向在线观众直播游戏或体育赛事[95]（图1(c)）。此类协同移动具有双重优势：一方面，将移动控制权交由他人可帮助被动用户节省导航消耗的时间与体力，使其更专注于其他交互任务；另一方面，主动用户能够扮演导游、体验分享者等角色。

可以消除协调路线和检查掉队者的需求。
然而，协同移动在主动与被动用户之间带来了独特的体验差距挑战。具体而言，在虚拟现实中移动时的感官冲突问题在被动视角下更为突出，相较于主动控制移动，

被动用户无法预知其下一步的运动或旋转，
导致输入意图与输出反馈之间的脱节[75]；主动用户采用的各种移动方法与被动用户叠加的各种移动（如静止站立[72], 环顾四周

[34]）可能进一步扩大主动用户与被动用户之间的体验差距被动用户。

人类移动通常伴随着复杂的感知运动整合过程[5]。在此过程中，大脑动态地为视觉、前庭和本体感觉信号分配不同的权重[60]:接收到的感觉信号越可靠，其权重就越高[28, 29, 45]。最终，

大脑通过考虑移动意图和生活经验等优化感觉信息，以提高认知准确性[59, 76]。虚拟现实移动通常伴随着感官冲突，尤其是采用不恰当的移动方法时，此类感官冲突已被证明会干扰用户的

空间意识、乐趣、自我运动感觉和存在感，并引发晕动症，其程度与移动形式[11, 62, 79]密切相关。例如，无感官冲突的实体行走比缺乏前庭刺激的手势或操纵杆移动[69, 80]具有更优的移动体验；多种移动类型（如平移与旋转）、方向、速度及个体差异会显著影响感官冲突与移动体验[17, 18, 35, 88]。先前研究探讨了不同感官刺激与感官冲突类型对移动体验[31, 54, 62, 105]的影响，但未能探究协同移动体验中主动与被动用户在不同移动场景下感官冲突的微妙影响。上述经验差距不利于团队和谐与协作任务效率，甚至削弱用户参与协同移动的动机。因此，明确各类协同移动情境中主动与被动用户间的经验差距至关重要。

在我们的用户研究中，我们根据主动与被动用户的运动病易感性 (MSS) 进行配对。我们依据主动用户的移动方法（行走、飞行操纵杆和瞬移）以及被动用户的可能行为（静止站立和环顾四周）设置了6种条件。在每种条件中，我们提取了主动/被动用户在完整移动过程中可能的独立动作作为子运动（例如，主动用户的一次平移/旋转，或被动用户的一次静止站立/环顾四周动作）。我们将这些子运动组合起来创建一系列运动节点，重点关注那些具有显著临时体验差距的节点。这些节点作为值得注意/可避免/可干预的情境，为条件中整体体验差距的归因提供了洞察，因为它是从一系列临时体验中累积而来的。我们调查了生理舒适度（即头晕、恶心和眼部不适等不适感较弱）、心理舒适度（即恐惧、不安和陌生感等不适感较弱）、存在感（即，

用户相信他们存在于虚拟世界中）、移动感知（即用户认为他们处于视图中呈现的运动状态）以及每个运动节点的可接受性（即用户能够接受这种移动的综合感受并愿意在未来协同移动中频繁体验），同时通过三份主观后测问卷了解用户在每种条件下体验所有节点后的整体感受。

最终，我们的分析考虑了不同条件、子运动组合、速度和MSS对体验的影响

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

差距，识别出被认为不可接受的移动情境
主动或被动用户。

总体而言，被动用户的体验比主动用户更差，
在涉及主动用户使用瞬移进行离散运动而被动用户静止站立的条件下，体验差距通常较小；而涉及被动用户环顾四周的条件和子运动组合往往会产生更大的体验差距。值得注意的是，感官差距在主动用户转动而被动用户环顾四周的子运动组合中尤为明显。有趣的是，当主动用户的平移与被动用户的头部旋转方向相似时，

被动用户的存在感和运动感觉甚至超过了主动用户。我们推测这些结果源于感官冲突类型与程度差异以及主动与被动用户间移动意图的综合影响。测量此类体验差距可带来3项重要研究意义：1) 理解不同共同运动情境下体验差距的差异，为VR多用户应用设计提供宝贵参考；2) 为避免/干预多用户协同移动中可能导致不适体验的行为提供指导；3) 深化对人类感知系统如何响应各类共同运动场景的理解。据我们所知，本研究首次全面考察了主动与被动用户在不同共同运动场景（涵盖多种感官冲突类型和程度）中的体验差距，特别是子运动组合的临时体验差距。本文作出以下三项贡献：

i) 定义多用户虚拟现实应用中的典型协同移动情境，以及相关的影响因素。

ii) 系统探索主动与被动用户在不同移动条件和子移动组合下的体验差距，以及各种因素对这些差距的影响，并基于感觉运动整合的知识分析可能的原因。

iii) 根据主动与被动用户在可接受性上的差异，识别值得注意、需避免和干预的协同移动情境。

2 相关工作

2.1 单用户移动

虚拟现实中的单用户运动方法和体验已得到广泛研究。单用户移动通常根据控制能力[77]分为主动移动和被动移动。

对于主动移动，用户通过具身或人工方法[8, 13]控制移动。具身方法包括躯干倾斜[40, 104]、、摇头[89]、、轻敲[68], 和头部操纵杆[41],

游泳[14], 和原地行走 [56, 101], 提供了自然的本体感觉和前庭刺激[30, 31]。多种人工移动方法，包括采用驾驶隐喻的方向盘/操纵杆以及瞬移，提供了替代方案。操纵杆和方向盘方法被认为省力，但可能导致

感官冲突会影响空间意识和运动不适感[3, 54, 63, 105]。瞬移通过即时改变自身位置，避免了持续移动，从而减少感官冲突[11, 33]。此外，手动/自动控制移动[57] 以及身体化身[81] 也有助于提升移动体验。

被动移动的研究少于主动移动，通常涉及用户观看电影/360度视频等虚拟现实内容，

沿着预设路线移动，或在汽车中使用虚拟现实[38, 39, 43, 72, 78]。由于移动能力受限，被动用户主要静止站立、环顾四周或进行阅读等原地任务[34, 72, 77]。被动移动因感官冲突和不可预测的运动更容易引发晕动症[61]。

这些研究启发了我们实验条件的动机与设置。值得注意的是，广泛使用的单用户运动方法，如主动移动中的行走、飞行操纵杆和瞬移，以及被动移动中的静态和环顾四周，

预计将在未来的多用户协同移动场景中发挥重要作用。此外，这些移动方法所伴随的多样化感官冲突促使我们探索由不同主动与被动移动方法及行为组合所产生的体验差异。

2.2 多用户移动

与已被广泛研究的单用户移动不同，多用户移动仍是一个小众领域，近期才有研究进展。一种直接的方法是允许每位用户独立导航[58]。在此模式下，由于不存在被动用户，研究通常聚焦于多个主动用户并发移动时的碰撞避免[2]。策略包括动态调整行走路径以防止碰撞[24, 44, 58]。另一种方法则是被动用户将移动控制权委托给主动用户以实现协同移动。

正如Weissker等人在其综述[97]中指出的，这种方式能增强协调性、减少被动用户的干扰，并降低掉队风险。

现有关于这种协同移动模式的研究通常聚焦于三个方面。首先，创新的群体移动方法旨在提升用户移动体验，例如采用带编队控制的群体瞬移来避免虚拟环境中的碰撞[99]、、运用握手隐喻实现灵活的用户绑定[98]，，以及通过结合地面代理与全身表示的"魔毯"技术实现逼真飞行体验[66]。其次，社交方法被设计用于改善用户间移动意图的沟通，包括可视化共享移动意图[74] 和运用多射线跳跃技术[96]。然而，对于需要频繁移动的大型或动态场景，每次子运动前预先沟通意图会导致高昂的沟通成本并降低导航效率。

第三，部分研究记录了主动用户的第一人称驾驶视频，将其回放给被动用户以模拟同步多用户共位移[15, 16, 21]。我们的研究采用类似方法，在模拟同步协同移动时分别评估主动与被动用户。然而，这些研究主要评估移动意图对运动

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

晕动症诱发时间的影响，且视频格式限制了动作
被动用户的能力，例如环顾四周。

本文中，我们的重点在于评估现有的协同移动方法而非引入新方法，这主要基于两个关键原因。首先，无论是新兴还是成熟的协同移动方法，它们都共享相似的感知机制，导致体验差距。因此，理解这些差距、其成因以及现有方法的局限性，对于改进旧方法或提出新方法至关重要。其次，当前关于虚拟现实共同运动的研究

缺乏对意图之外的影响因素和晕动症之外的评估指标的全面考量。因此，我们的研究探索了更广泛的条件范围，并强调了感觉运动冲突的影响，同时纳入了多样化的体验指标。

2.3 晕动症

晕动症在实际和虚拟移动过程中频繁发生，表现为头晕、出汗、

眼部不适及呕吐等症状。目前有三种理论解释晕动症机制：姿势不稳定理论[86]、、poi-son理论[92]，以及感觉冲突理论[51]。其中接受度最高的是感觉冲突理论，认为大脑难以处理多感官感知到的不匹配移动状态信息，从而引发不适的生理反应[46, 55, 64]。该理论是本文解释晕动症及暂时性生理不适成因的基础。

晕动症程度受各种因素影响。移动方法类型会影响晕动症发作时间及严重程度；例如，连续视觉运动比离散视觉运动更易诱发晕动症[65]。此外，被动运动较主动运动更易引发晕动症[84]。子运动的类型与参数（包括旋转/平移、运动方向、多轴/单轴）

振荡/非振荡、高速/低速、长时间/短时间等因素也起着重要作用[4, 9, 25, 52]。个体差异，如晕动症易感性、年龄、性别等，

进一步增加了晕动症影响因素的复杂性[22, 35]。

晕动症通常通过基于不适症状[47], 的后测量表SSQ进行评估，而其易感性则通常通过基于生活经验[36]的MSSQ问卷测量。

由于晕动症的诱发及其进一步恶化依赖于子运动引起的感觉运动冲突的持续累积，FMS旨在评估由感官冲突[48], 引发的此类不适感受的动态变化过程，即每隔一段时间调查一个单问题量表（即生理不适的总体水平）。其中，当运动状态发生变化时，某些生理不适感受会在极短时间内显著增强/减弱[6, 67, 93], ，例如从静态到移动、从移动到静态、从平移到旋转以及速度变化等。

这些研究为我们的子移动组合、因素及评估方法的实验配置提供了依据。它们

同时也对我们关于晕动症的结果归因有所贡献
暂时性生理不适。

3 设计考虑与预实验

本节通过引入对移动配置的考量（包括条件、子移动类型及影响因素），强化了正式实验的设计。同时基于预实验结果，提出了适宜的运动参数建议。

3.1 设计考虑

参考2.1节所述的单用户运动方法，
实体行走作为连续体现运动的典型方法，不会引发感官冲突[69]。飞行操纵杆适用于有限物理空间，通过驾驶隐喻实现连续移动，但可能产生视觉-前庭冲突[102]。瞬移技术因能实现即时位置和方向变化而广受欢迎，其为用户提供具有最小感觉刺激的离散运动方法[33, 73]。在正式实验中，我们为主动用户选择行走、飞行操纵杆和瞬移，而被动用户则执行静止站立和环顾四周等基本动作（分别对应表1的第1列和第5列）。

典型的行走亚运动包括向前移动、侧向移动以及左/右转。飞行操纵杆的亚运动则涵盖向前移动、侧向移动、上/下移动、左/右转、上/下转动以及左/右滚动。瞬移亚运动则包含位置变更[11] 以及位置与方向同时变更[96, 99]。这些动作在正式实验中被指定为主动用户的子运动（见表1第2列）。而典型的环顾四周行为，即被动用户上下左右转动头部，在正式实验的观察中被视为被动用户的亚运动（见表1第6列）。

考虑到所概述的影响感觉运动冲突的因素
在第2.3节中，诸如移动速度、瞬移等参数
间隔、运动时间和MSS被普遍认为是
对移动体验[53, 83]具有重要影响。为了评估
不同运动参数组合对
体验差距的影响，基于预实验结果，我们设定了两个

数值（一大一小）作为速度/瞬移间隔的
每个子运动的正式实验参数。考虑到
协同移动时间对于主动与被动用户
在每个子运动组合中保持一致且具有清晰易辨的
可预测的影响，因此不作为自变量
在正式实验中。此外，探究
MSS对体验差距的影响被认为具有价值。因此，在
正式实验中，我们将主动与被动用户
的组合分为四组，即易眩晕-不易
头晕，不易头晕-易眩晕，不易
易眩晕 - 不易头晕，以及易眩晕 - 易眩晕。

3.2 预实验

开展预实验的目的是为正式实验中每个子运动确立合适的运动参数，

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	3 m/s & 6 m/s (6)	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
	go left/right	4 m/s & 8 m/s (2)					
	go up/down	5 m/s& 10 m/s (0)					
	turn left/right	20 °/s & 40 °/s (2)	25 °/s & 50 °/s				
	turn up/down	25 °/s & 50 °/s (5)					
	roll left/right	30 °/s & 60 °/s (1)					
teleportation	alter position	1 s & 2 s (1)	1.5 s & 3 s				
	alter position & orientation	1.5 s & 3 s (6) 2 s & 4 s (1)					

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)).

表1：基于设计考虑与预实验确定的正式实验移动配置

	主动用户			被动用户			
移动方法	子移动	可选速度/间隔	确定速度/间隔	叠加移动	Sub-移动	可选速度	确定速度
行走	向前走	0.5 米/秒 & 1 米/秒 (2) 0.6 米/秒 & 1.2 米/秒 (4) 0.7 米/秒 & 1.4 米/秒 (2)	0.6 米/秒 & 1.2 米/秒	静止站立	静态	0	0
	侧向行走	0.3 米/秒 & 0.6 米/秒 (3) 0.4 米/秒 & 0.8 米/秒 (5) 0.5 米/秒 & 1 米/秒 (0)	0.4 米/秒 & 0.8 米/秒				
	左转/右转	20 度/秒 & 40 度/秒 (2) 25 度/秒 & 50 度/秒 (4) 30 度/秒 & 60 度/秒 (2)	25 度/秒 & 50 度/秒				
飞行操纵杆	前进	3 米/秒 & 6 米/秒 (6)	3 米/秒 & 6 米/秒	环顾四周	上下转动 左右转动	20 度/秒 & 40 度/秒 (1) 25 度/秒 & 50 度/秒 (3) 30 度/秒 & 60 度/秒 (4) 30 度/秒 & 60 度/秒	
	向左/右转	4 米/秒 & 8 米/秒 (2)					
	向上/下移动	5 米/秒 & 10 米/秒 (0)					
	左转/右转	20 度/秒 和 40 度/秒 (2)	25 度/秒 和 50 度/秒				
	调高/调低	25 度 /秒 和 50 度 /秒 (5)					
	左右滚动	30 ° /s 和 60 ° /s (1)					
瞬移	改变位置	1秒与2秒 (1)	1.5秒与3秒				
	改变位置 和方向	1.5秒与3秒 (6) 2秒与4秒 (1)					

使实验设置更贴近实际的协同移动场景。八名参与者（4名男性，

4名女性（平均年龄= 23.5岁，标准差= 4.04，年龄范围：18-29岁）来自本地大学参与了预实验。我们为每个子运动（表1第3列和第7列）设计了三对可选速度（3慢速和3快速）/传送间隔（3大和3小）。其中，为更好衡量速度/传送间隔对运动间隙的影响，每对数值中较大值是较小值的两倍；这些可选数值直接选自或略微修改自部分运动相关文献中的常见运动参数设置，例如前进速度[7, 70],

侧移速度[19], 行走/飞行/环视时的转向速度[12, 37, 80], 飞行操纵杆平移速度[27, 66],

以及瞬移的传送间隔[20]。参与者在正式实验场景中体验每个子运动的各可选速度后，选出他们认为最适合且偏好多用户共同运动场景的速度/间隔组合。

最后，我们统计了参与者对每个速度/瞬移间隔组合的选择（表1中括号内的蓝色数值），将选择次数最多的组合确定为正式实验的运动参数（表1中的第4和第8列）。

4 用户研究

本研究将主动与被动用户一对一配对，系统性地探索多样化运动场景中的体验差距，并评估各种因素的影响。

4.1 伦理与参与者

该实验获得了本地大学的伦理批准
并排除了患有前庭功能障碍或严重运动障碍的个体
晕动症症状。参与者完成了运动

晕动病易感性问卷（MSSQ [36]）。根据MSSQ的分类标准，总分>11.3及以上的参与者被归类为易眩晕人群。我们从4所本地大学招募了48名学生（25名男性和23名女性，平均年龄= 23.125岁，中位年龄= 23岁）。

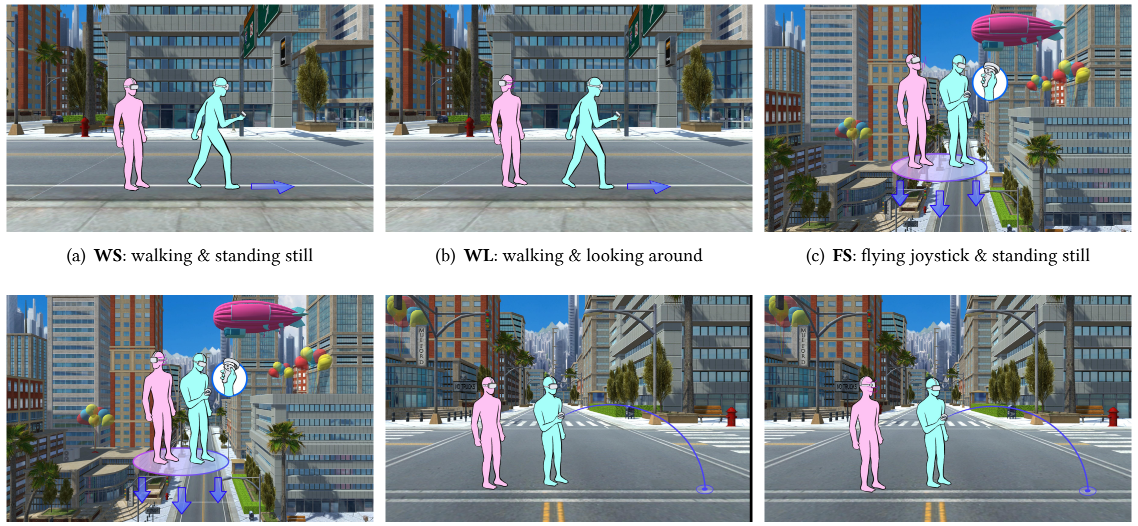
标准差 = 3.26，年龄范围：18-32岁）。参与者中，虚拟现实熟练度（每周使用VR超过5次）、部分熟练（每周使用VR少于5次）和无经验的分别为14人、18人和16人。其中，24人为主动用户（12人不易头晕，12人易眩晕），24人为被动用户（12人不易头晕，12人易眩晕）。

为测量主动与被动用户在不同MSS下的综合效应，我们将24名主动用户和24名被动用户配对组成
4种组合：6名易眩晕的主动用户和6名易眩晕的被动
用户、6名不易头晕的主动用户和6名不易头晕的被动用户、6名易眩晕的主动用户
易眩晕 和 6名被动用户 不易头晕，以及6名
主动用户 不易头晕 和 6名被动用户 易眩晕
。配对规则如下：对于前两种类型
的配对，主动与被动用户之间的MSSQ分数差异
需为<5；对于最后两种类型的配对，差异
在主动与被动用户之间的MSSQ分数需为>11.3 .

4.2 条件与运动节点

基于第3.1节讨论的移动方法与叠加行为
共设计了3*2=6 种条件：

- WS：主动用户行走，被动用户静止站立（图2(a)）。
- WL：主动用户行走，被动用户环顾四周（图2(b)).
- FS: 主动用户通过操纵杆飞行，被动用户静止站立(图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:

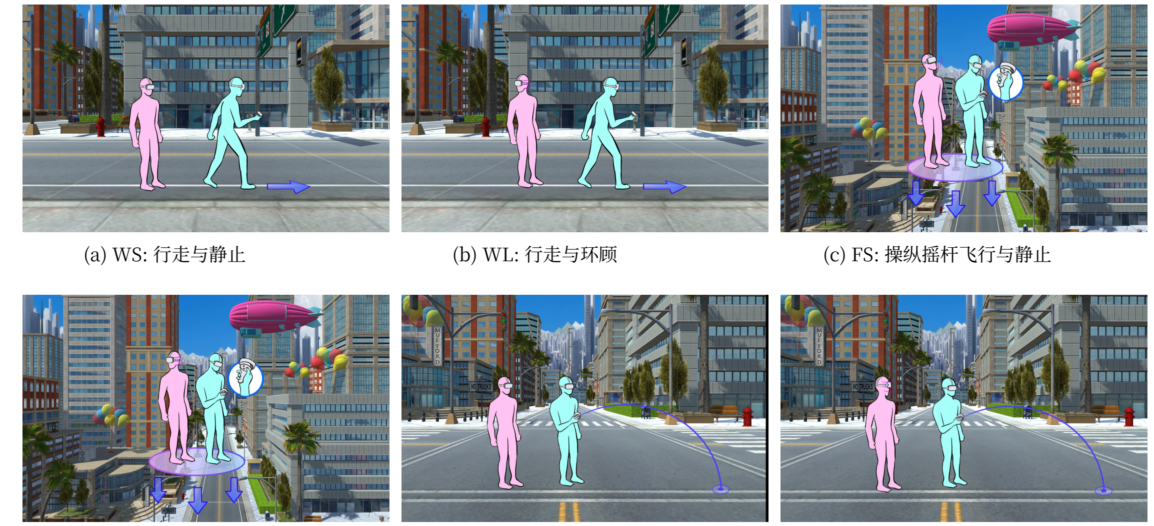
- **WS**: 3 types of active user (walk forward, walk sideways, turn left/right) * 2 speeds (0.6 m/s & 1.2 m/s, or 25 °/s & 50 °/s) * 1 type of passive user (standing still) = 6 nodes
- **WL**: 3 types of active user (walk forward, walk sideways, turn left/right) * 2 speeds (0.6 m/s & 1.2 m/s, or 25 °/s & 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) WS: 行走与静止 (b) WL: 行走与环顾 (c) FS: 操纵摇杆飞行与静止

(d) FL: 操纵摇杆飞行与环顾 (e) TS: 瞬移与静止 (f) TL: 瞬移与环顾

图2: 6种条件对应主动用户移动方法与被动用户行为的各种组合。

- FL: 主动用户通过操纵杆飞行，被动用户观察环顾四周（图2(d)）。
- TS: 主动用户瞬移，被动用户静止站立（图2(e)）。
- TL: 主动用户瞬移，被动用户环顾四周（图2(f)）。

如第2.3节所述，评估子运动过程中的情感动态变化对于理解整体体验及识别值得关注的运动情境至关重要。为衡量主动与被动用户之间的临时体验差距，我们通过结合子移动类型与参数，为每种条件创建了一组运动节点：

- WS：3种主动用户类型（向前走、侧向行走、左转/右转）* 2 速度（0.6 米/秒 & 1.2 米/秒，或 25 度/秒 & 50 度/秒）* 1 类被动用户（静止站立）= 6 节点
- WL：3种主动用户（向前走、侧向行走、左转/右转）* 2种速度（0.6 米/秒 & 1.2 米/秒，或 25 度/秒 & 50 度/秒）* 2种被动用户（头部上下转动、头部左右转动）* 2种速度（30 度/秒 & 60 度/秒）= 24 节点
- FS: 6种主动用户（前进、向左/右转、向上/下移动、左转/右转、调高/调低、左右滚动）* 2种速度（3 米/秒 & 6 米/秒，或 25 度/秒 & 50 度/秒）* 1种被动用户（静止站立）= 12 节点
- FL: 6种主动用户（前进、向左/右转、向上/下移动、左转/右转、调高/调低、左右滚动）* 2种速度（3 米/秒 & 6 米/秒，或25 度/秒 & 50 度/秒）* 2种被动用户（头部上下转动、头部左右转动）* 2种速度（30 度/秒 & 60 度/秒）= 48 节点
- TS: 2种主动用户（仅改变位置、改变位置与方向）* 2种传送间隔（1.5秒与3秒）* 1种被动用户（静止站立）= 4 节点
- TL: 2种主动用户（仅改变位置，改变位置与方向）* 2种传送间隔（1.5秒与3秒）* 2种被动用户（头部上下转动，头部左右转动）* 2种速度（30 度/秒 & 60 度/秒）= 16 节点

4.3 实验场景、引导物体与运动控制方法

我们选择了一个具有丰富参考物体的城市场景作为实验环境，如图3(a)所示。值得注意的是，对于包含垂直移动的FS和FL，我们特意加高了城市建筑并添加了鸟群、气球和飞艇等空中物体，以保持与地面运动相当的视觉运动刺激。

为帮助参与者达成行走、瞬移和转头所需的运动参数，我们采用了引导物体。对于行走和环顾四周，一个直径0.25米的半透明球体被用作引导对象，其位置位于参与者前方2米处的视线高度。其目的是通过半透明设置使引导对象清晰可见，同时不遮挡背景提供的视觉刺激。该对象会根据运动节点的需求，按指定方向和速度围绕参与者移动或旋转（见图3(b)和(c)）。对于瞬移功能，则使用带红线的直径1米的圆盘红色线段和倒计时被用作地面上的引导对象（图3(d)）。圆盘位置指示瞬移位置，红色线段表示瞬移方向，倒计时则确保所需的瞬移间隔。

对于主动用户，行走涉及腿部物理运动，例如通过左腿向左移动并将右腿并拢实现侧向行走[19]。参与者需跟随引导对象的速度进行直线行走或身体旋转。

对于飞行摇杆移动，平移/旋转速度参数已在控制程序中设定。参与者使用摇杆和手柄上的按钮进行三自由度平移和旋转，其映射关系如图4(a)和(b)所示。平移/旋转

(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.

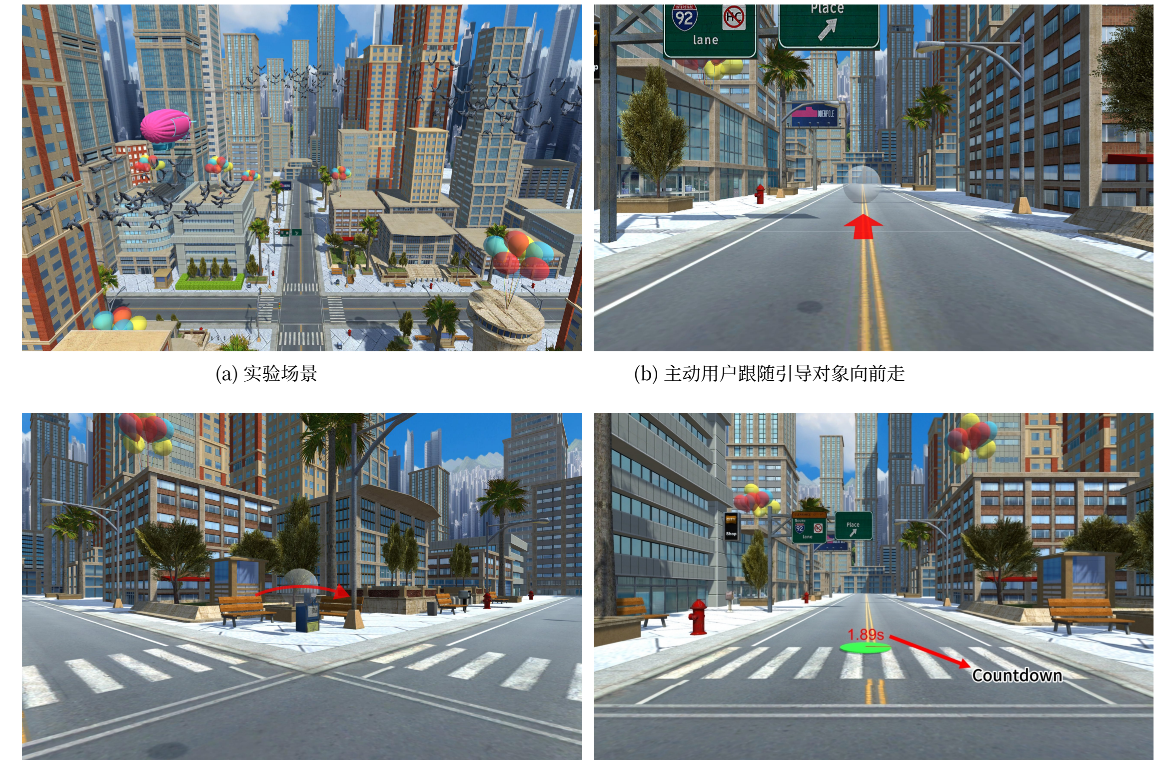
To reduce the influence of body posture, all conditions of the experiment were conducted in the standing position.

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) 实验场景 (b) 主动用户跟随引导对象向前走

(c) 被动用户跟随引导对象左右转动头部 (d) 用于传送位置、方向和间隔的引导对象

图3：实验场景与引导对象

方向被限制在全局坐标系的一个轴上，且操纵杆偏移量不会影响速度。瞬移功能需推动摇杆投射抛物线射线，传送目标显示为蓝色圆盘及指示方向的红色线段（图4(c)）。手柄位置与旋转控制传送目标，传送范围为0米至10米。操纵杆的偏移方向实时映射到瞬移目标的红色线段上以控制传送方向。每当引导对象出现时，参与者需在倒计时结束前将瞬移目标与引导对象对齐，并在倒计时结束时松开摇杆以激活瞬移。

被动用户的静止站立涉及在观察主动用户移动时保持不动状态。环顾四周是一种往复动作，要求参与者跟随引导物体，先将头部转向一侧，然后再将头部转向相反方向的另一侧...

直到运动节点结束。为确保参与者在转头过程中的舒适度，我们根据人类颈部运动的典型范围[85]为引导物体的往复运动设置了拐点：对于上下转头，拐点位于相对于中立位置的50°下和60°上；对于左右转头，拐点位于相对于中立位置的70°。

为减少身体姿势的影响，所有条件实验在站立姿势下进行。

4.4 流程

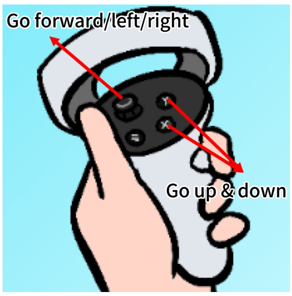
本实验采用重复测量，即参与者需在所有条件下完成所有运动任务。实验过程如图5所示。

为了平衡不同条件间的运动节点数量，我们将每种条件的运动节点增至48个——这是所有条件节点数的最小公倍数。具体方法包括：先随机抽取所有运动节点生成无重复的序列1，再重复抽取过程生成无重复的序列2并接续在序列1之后，如此循环直至序列1中的运动节点总数达到48个。每个运动节点的持续时间为8秒。

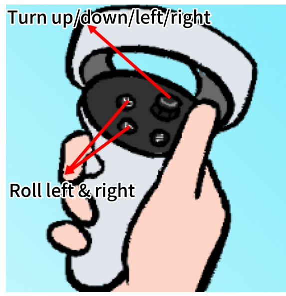
为减少多用户在线延迟和协作问题对研究结果的潜在影响，实验采用异步分离运动来模拟协同移动

同时适用于主动与被动用户。实验分为两个阶段：第一阶段由24名主动用户以平衡顺序完成所有条件中的运动节点，其运动数据（包括条件序列、节点序列）

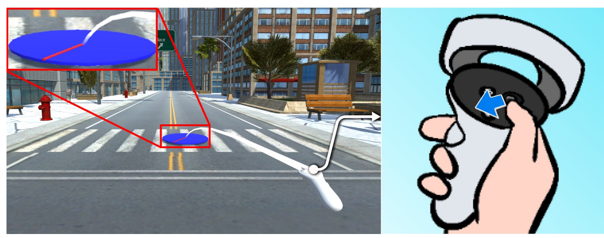
以及轨迹均被记录。在第二阶段，24名被动用户按照与其配对的主动用户相同的顺序执行相同的运动节点，



(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.

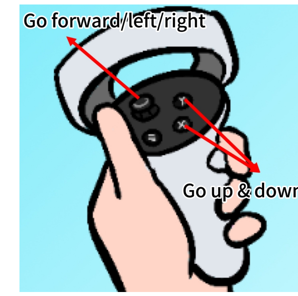
4.5 Measurements of Mitigating bias

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.

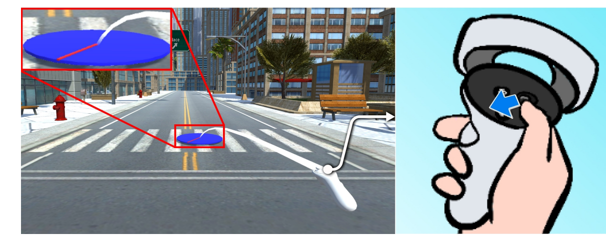
4.6 Implementation

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



(a) 飞行操纵杆的平移控制

(b) 飞行操纵杆的旋转控制



(c) 瞬移的位置与方向控制

图4：飞行摇杆与瞬移的控制方法

并将主动用户的移动轨迹应用于他们身上。图6(a)展示了WL中一名主动用户与一名被动用户连续执行运动节点（主动用户左转，被动用户上下环视）的过程。

实验过程中每隔一段时间仅填写一个问题的单项量表测量方法已被证明能更准确地捕捉瞬间/临时体验，并且相比多项量表[90, 94]对记忆衰退的敏感度更低。此类快速单项量表已广泛应用于评估晕动症[48], 存在感[10], 运动感觉[62],等临时体验。

遵循该方法论，参与者在完成每个运动节点后（图6(b)）对生理舒适度、心理舒适度、运动感觉、存在感和可接受性5个单项量表进行评分。可接受性量表仅允许0（不可接受）或1（可接受）的分数，其他量表范围为0-10。除可接受性外，参与者需为每个指标提供两个分数（移动前和运动中）。

我们采用运动中分数与运动前分数之差作为各指标得分，以消除运动节点间的累积影响。

当单项量表覆盖用户视野后，参与者会被重置到下一个运动节点的原点，为后续节点做准备。在FS和FL中，涉及向下平移的节点原点被设置在十字路口上方50米处，

而其他节点的原点则位于十字路口中心上方12米处。在其他条件下，所有原点均位于十字路口中心，无高度差。

由于单项量表的遮挡，参与者无法看到重置过程，以减少视觉刺激的潜在影响。

每个新运动节点开始时，参与者前方会出现一个箭头，指示即将进行的移动/转头方向。为模拟真实的协同移动，主动用户的箭头持续4秒以提供充分准备时间，而被动用户的箭头则随机持续2至6秒以增加不可预测性。箭头消失即提示参与者需启动与该节点对应的子运动。若运动节点包含引导对象，参与者需与其速度或瞬移间隔保持同步。

完成每种条件下的所有运动节点后，参与者退出虚拟现实环境并填写三份后测问卷，以评估该条件下的整体移动体验：模拟器疾病问卷SSQ [47] (0-3)、存在感量表[82] (0-10)、

以及一份自定义问卷，包含三个关于运动感觉(0-10)、心理舒适度(0-10)和可接受性(0-1，其中0表示不可接受，1表示可接受)的问题，如表2所述。最后，参与者接受访谈，表达他们对运动节点和条件的感受。

4.5 减轻偏差的测量

为确保参与者理解实验内容，我们在实验开始前提供了全面的介绍。这包括实验过程、条件、整体体验量表、运动节点以及与临时体验相关的五项单项量表的详细信息。此外，我们还展示了展示运动控制方法的演示视频，并解答参与者的问题，直到他们对实验感到熟悉为止。随后，我们对测量临时体验的五项单项量表向参与者进行了澄清：生理舒适度指的是头晕、恶心和眼痛等生理感觉中不适的强度；心理舒适度意味着恐惧和不安等心理感受中的不适；存在感反映了参与者认为自己在虚拟世界中的程度；运动感觉表示参与者在视图中感知自己处于运动状态的程度，而可接受性则衡量了参与者

对运动节点的整体感受以及他们在未来协同移动中频繁体验的意愿。此外，对于包含多项的三项后测问卷，我们提供了每项的详细解释以消除歧义。

为减轻潜在影响和学习效应的影响，
我们采用平衡顺序安排参与者体验不同条件。在条件转换间，参与者

被要求休息直至任何主观不适和疲劳

消退，以减少遗留效应。我们会口头确认
他们已恢复至实验前状态，再继续进入

下一条件。参与者可获得40美元现金奖励，即使他们
因不适退出实验。四名参与者
终止了实验，我们招募了四名替代者
其MSSQ分数相近。

4.6 实施

采用Unity引擎v.2020.3.36f1c1开发移动控制方法、预实验及正式实验。

主动用户的运动轨迹数据以JSON文件形式存储。
被动用户的叠加视图是通过将

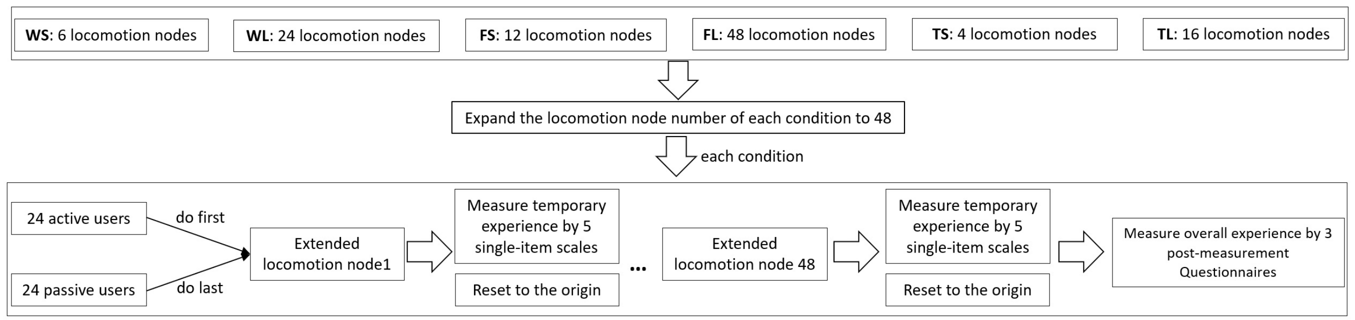
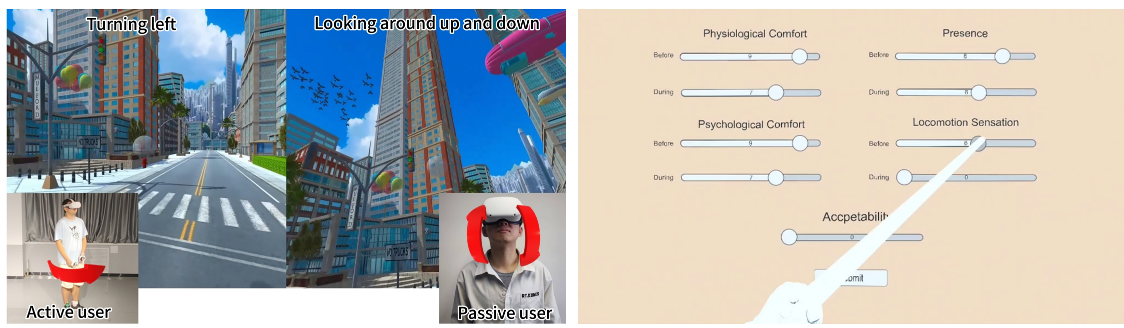


Figure 5: The experimental procedure of user study



(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 main-Camera. 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.

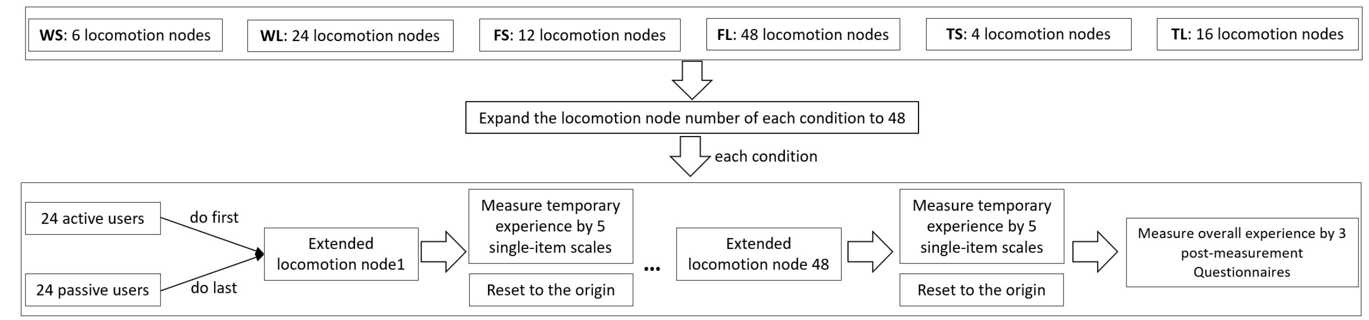
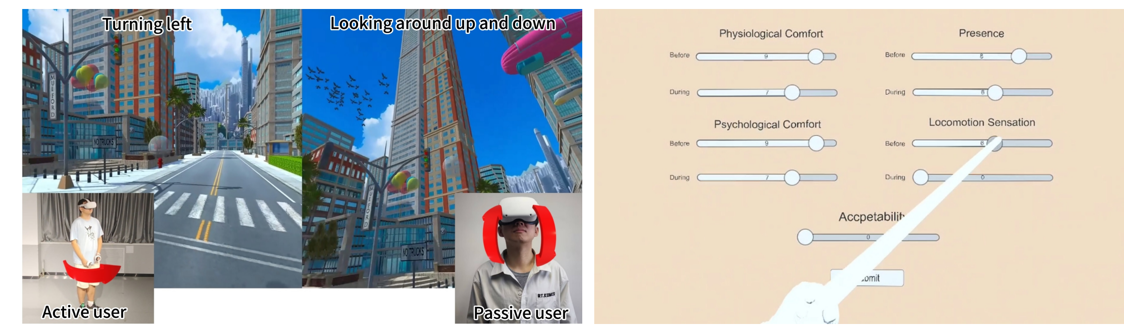


图5：用户研究的实验流程



(a) 两名参与者依次完成WL中的移动节点 (b) 在每个移动节点后填写5个单项量表

图6：实验过程演示

表2：用于测量每种条件后整体体验的定制后测问卷

问题编号	
1	在此条件下，你在多大程度上感觉/相信自己始终处于视野中呈现的运动状态?
2	在此条件下，你是否很少经历强烈的恐惧、不安和陌生感?
3	你能接受运动的综合感受并愿意频繁使用此条件吗?

活跃用户的运动轨迹应用到主摄像机（main-Camera）的父对象上生成的。实验采用了四台Oculus Quest 2头戴设备[87]，并为主动用户提供了足够大的室内空间以供行走。

5 结果

总计，我们收集了48（参与者数量）*6（条件数量）*48（运动节点数量）*5（单项量表数量）= 69120 运动节点的临时体验数据，以及48（参与者数量）*6（条件数量）*3（问卷数量）= 864 后测问卷的整体体验数据。

由于大部分数据根据

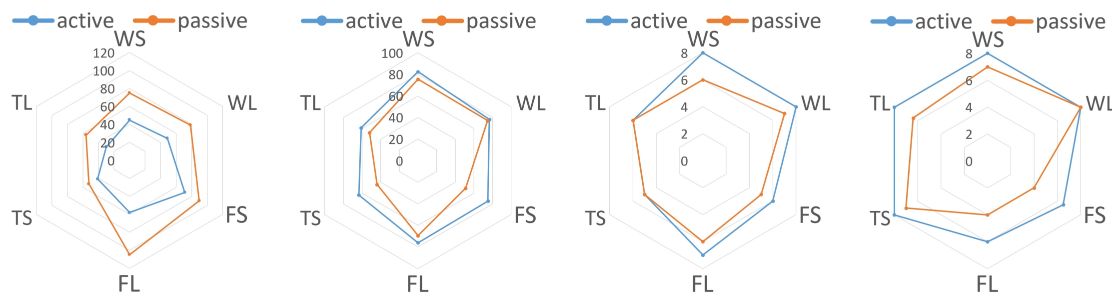
Shapiro-Wilks检验结果不服从正态分布，我们采用中位数作为整体数据的代表性指标。我们使用雷达图展示每种条件下主动与被动用户间的中位数差异，箱线图则用于呈现体验数据的中位数及数据分布情况绘制体验中位数及数据分布的图表间隔，以及表格展示各子运动组合中体验差距的中位数数值

对于条件接受度，考虑到鉴于数据的二元性质（0和1），我们采用了百分比堆叠条形图展示评分参与者的比例分布。此外，我们运用了Wilcoxon符号秩检验来判定主动与被动用户之间在每种条件/子运动组合中的显著差异，并以Wilcoxon检验的r值作为其效应量[32]Friedman检验及事后两两比较（Dunn法）方法及Bonferroni校正[26]）在SPSS中，评估了不同条件对体验差距的显著性差异，

以Kendall W检验数值作为效应量[91]。Bonferroni校正被选用来降低家族误差率，特别是在条件数量相对较多的情况下[1]。

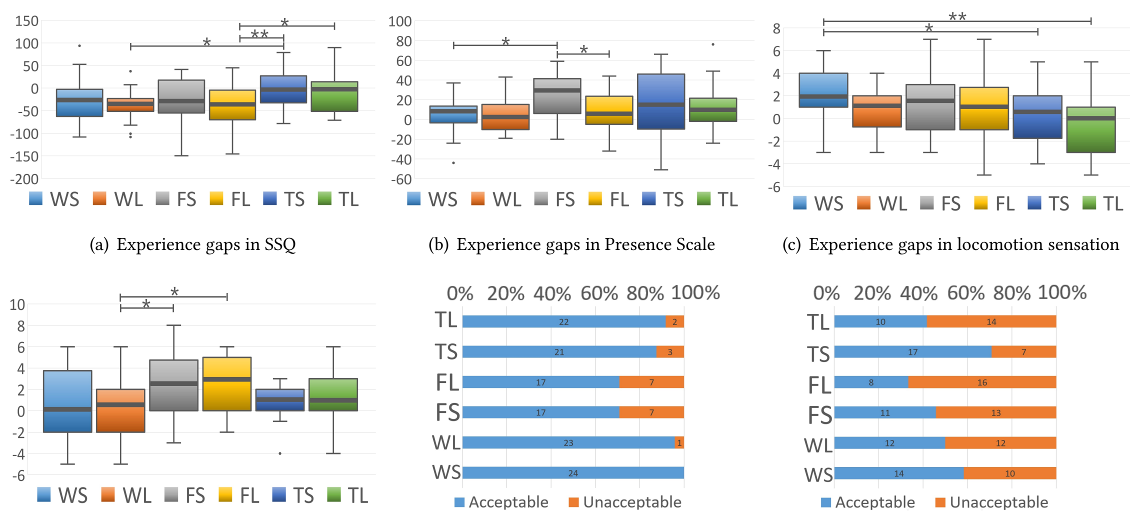
5.1 主动与被动用户在后测问卷中的体验

本节旨在以视觉方式呈现主动与被动用户在每种条件下的体验，并报告显著差异。



(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

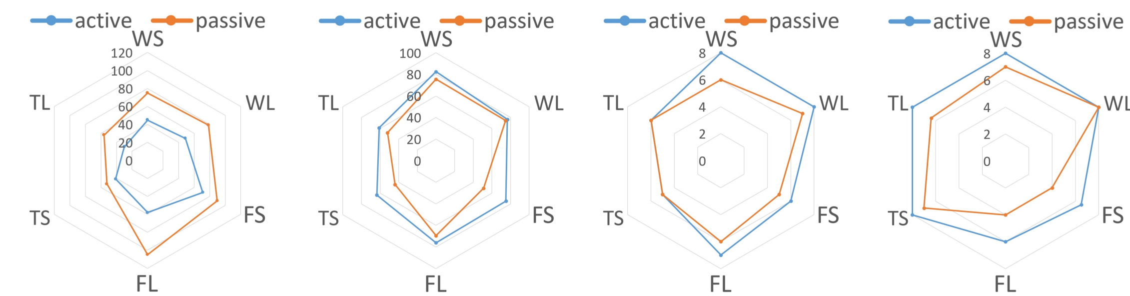
We computed the total SSQ score using the original paper's method [47] and the total Presence Scale score by summing all item scores. Median values for total SSQ score, total Presence Scale score, and scores for locomotion sensation and psychological comfort in the Custom Questionnaire were illustrated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

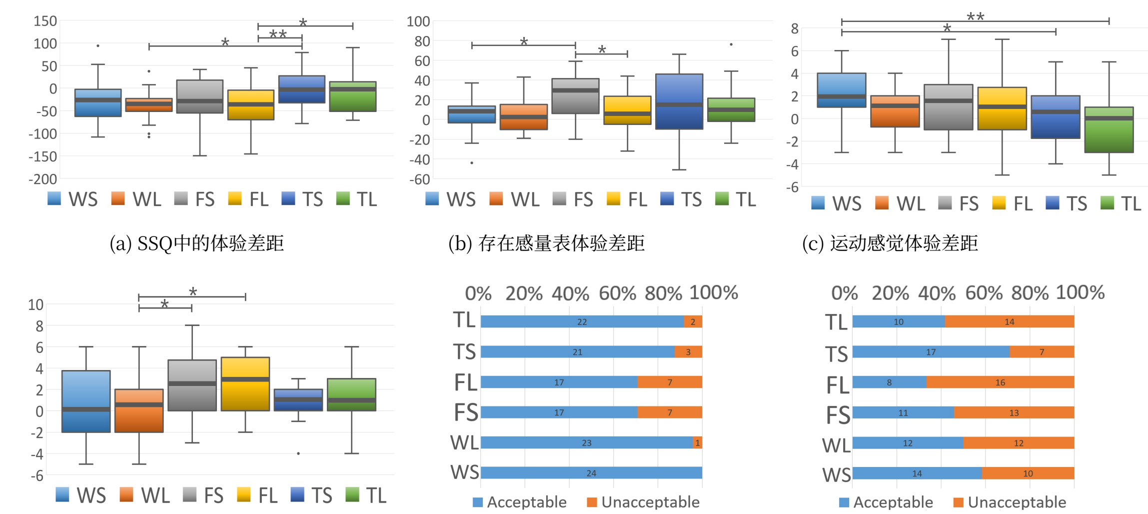
5.2 Experience Gap of Various Conditions in Post-measurement Questionnaires

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.



(a) SSQ总分 (b) 存在感量表总分 (c) 运动感觉得分 (d) 心理舒适度得分

图7：每种条件下主动与被动用户的后测问卷得分



(a) SSQ中的体验差距 (b) 存在感量表体验差距 (c) 运动感觉体验差距

(d) 心理舒适度体验差距 (e) 主动用户接受度 (f) 被动用户接受度

图8：后测问卷中主动与被动用户之间的体验差距

我们采用原始论文的方法[47] 计算了SSQ总分，并通过累加所有项目得分得出存在感量表总分。

采用四幅雷达图（图7）展示了自定义问卷中SSQ总分、存在感量表总分以及运动感觉和心理舒适度评分的中位数数值。

Wilcoxon符号秩检验结果显示，在SSQ总分方面，主动与被动用户在WS（$Z = 2.388$, $p = .017$, $r = .345$）、WL（$Z = 3.846$, $p < .001$, $r = .555$）、FS（$Z = 2.186$, $p = .029$, $r = .315$）上存在显著差异，

以及FL（$Z = 3.514$, $p < .001$, $r = .507$）；在存在感量表总分中，主动与被动用户在FS（$Z = -3.688$, $p < .001$, $r = -.532$）、TS（$Z = -2.1$, $p = .036$, $r = -.303$）和TL（$Z = -2.401$, $p = .016$, $r = -.346$）方面存在显著差异；在运动感觉评分中，主动与被动用户在WS（ $Z = -3.509$ $p <$ 001 $r =$, .,）和 $-.506$ $Z = -2.988$ $p =$ 003 $r = -.431$ FS（, .,）方面存在显著差异；在心理舒适度评分中，主动与被动用户在FS（$Z = -3.385$, $p = .001$, $r = -.488$）方面存在显著差异，

FL（$Z = -3.459$, $p = .001$, $r = -.499$），以及**TL**（$Z = -2.371$, $p = .018$, $r = -.342$）。

总体而言，在所有条件下，至少存在一项体验指标的显著差异。FS在所有体验指标上均表现出主动与被动用户间的显著差异，

而TS仅在存在感方面表现出显著差异。

5.2 后测问卷中不同条件的体验差距

本节通过视觉化方式呈现每种条件下的体验差距及其数据分布，并比较条件间的显著差异

这些结果可作为识别需要进一步分析和改进的条件的参考依据，特别是那些存在更明显差距问题的条件，以及差距较小的条件。适合直接使用于协同运动场景。经验差距数值计算方式为活跃用户的问卷分数减去被动用户的分数，用于箱线图和显著性分析。

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

表3：各种子移动组合的临时体验差距。表中*Sig.* 表示显著差异；紫色代表罕见负差距的子运动组合；绿/黄色表示主动与被动用户旋转轴不同/相同时部分指标存在显著差距的子运动组合；蓝/红色分别代表主动用户可接受但被动用户不可接受或双方均不可接受的情况。

条件	子运动组合		生理舒适度		心理舒适度		存在感		运动感觉		可接受性百分比	
	主动	被动	Sig.	Gap	Sig.	Gap	Sig.	Gap	Sig.	Gap	主动	被动
WS	前进	静止站立	**	1	/	0	/	0	***	2	99%	72%
	向左/右转	静止站立	/	1	/	0	/	0	*	1	86%	63%
	左转/右转	静止站立	***	2	/	1	/	0	**	2	92%	48%
WL	前进	头部上下转动	/	0	/	1	/	-1	**	-2	98%	80%
	向左/右转	头部上下转动	*	1	/	1	/	1	/	0	88%	66%
	左转/右转	头部上下转动	***	4	**	1	**	1	/	1	94%	45%
	前进	头部左右转动	*	1	/	0	/	0	*	1	99%	81%
	向左/右转	head turn left & 右转	**	1	/	1	/	0	/	-1	89%	77%
	左转/右转	头部左转 和 ri ght	**	3	***	3	**	2	***	3	93%	34%
FS	前进	静止站立	*	1	/	1	**	2	*	1	86%	62%
	向左/右转	静止站立	/	0	*	2	*	1	/	0	82%	63%
	向上/下移动	静止站立	/	1	**	1	/	1	*	1	80%	57%
	调高/调低	静止站立	**	2	**	2	*	1	*	1	78%	53%
	左转/右转	静止站立	*	2	/	1	*	2	**	2	74%	59%
	左右滚动	静止站立	***	3	***	2	***	2	**	2	43%	38%
FL	前进	头部上下转动	*	1	*	1	**	-2	*	-1	85%	69%
	向左/右转	头部上下转动	/	0	**	2	*	1	/	1	81%	58%
	向上/下移动	头部上下转动	*	1	***	3	*	-1	*	-1	84%	45%
	turn 上/下	head turn up & down	***	3	**	2	**	2 ***		3	84%	43%
	左转/右转	头部上下转动	***	2	/	1	**	1	/	1	77%	42%
	左右滚动	头部上下转动	***	3	***	3	*	1	/	0	49%	28%
	前进	头部左转 和 ri ght	/	1	/	1	/	1	/	1	83%	65%
	向左/右转	头部左右转动	*	2	/	1	/	0	*	-2	82%	70%
	向上/下移动	头部左右转动	/	1	***	3	/	0	/	1	79%	59%
	turn 上/下	头部左右转动	***	2	***	3	*	1	*	2	83%	36%
	左转/ri ght	头部左右转动	**	2	/	0	***	3	***	3	81%	29%
	左右滚动	头部左右转动	***	4	***	3	*	2	*	2	47%	35%
TS	改变位置	静止站立	/	0	/	0	***	2	/	0	92%	78%
	变更 pos & ori	静止站立	/	0	/	0	***	3	/	1	90%	72%
TL	变更位置	头部上下转动	*	-1	/	0	/	1	*	-1	93%	64%
	变更 pos & ori	头部上下转动	/	0	**	1	**	2	/	-1	88%	44%
	改变头部位置	turn left & 右转	/	1	**	2	*	2	/	-1	90%	46%
	改变位置 和 原始	头部左右转动 *		1	**	2	**	2	/	1	89%	41%

弗里德曼检验结果显示，模拟器疾病问卷（SSQ）得分（ χ^2 5 = 20.145 p = 001 W = .336 χ^2 5 = 14.025 p = ()、.、）、存在感量表（Presence Scale）得分（( )，.015， W = .234）、运动感觉（locomotion sensation）得分（χ^2 (5)= 17.287， p = .004， W =

.288 χ^2 5 = 18.258 p = 003 W = ），
.304
以及心理舒适度（ () , . , ）受条件影响显著。体验差距数据的箱线图及通过配对比较得出的条件间显著差异如图8(a)-(d)所示，其中*代表p < .05，**代表p < .01，***代表p < .001。

此外，主动与被动用户的可接受性结果以百分比堆叠条形图形式呈现（图8(e)和(f)）。根据主动用户的可接受比率减去被动用户的可接受比率，可得出

WS、WL、FS、FL、TS和TL的可接受性差距分别为50%、29.1%、37.5%、25%、45.8%分别为41.7%。

总体而言，FL在晕动症和
心理舒适度上表现出最大差距，FS的存在感差距最大，而WS的运动感觉差距最为显著。关于
可接受性方面，所有条件下的多数主动用户认为移动方式可接受，但超过半数的被动用户无法接受

在WL、FS、FL和TL中。

5.3 不同场景下的临时体验差距 子运动组合

本节旨在直观呈现临时体验
主动与被动用户在每种子运动间的体验差距

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**.

组合在每种条件下的表现。一方面，这有助于研究者理解不同子运动组合的表现效果及各类感官冲突类型的影响差异；另一方面，这为本文分析条件整体体验差距的成因提供了依据，并筛选出值得关注/规避/干预的体验差距较大的子运动组合。

首先，我们将运动节点按主动与被动用户的形式划分为多种子运动组合（参见表3）。接着，我们通过从运动中分数减去运动前分数，计算出每位主动与被动用户的临时体验分数。临时体验差距分数则是通过从主动用户的临时体验分数中减去被动用户的临时体验分数得出。该表包含威尔科克森检验的显著性结果（*Sig.*）及临时体验差距的中位数值（*Gap*）。此外，最后两列展示了主动与被动用户对各子运动组合的可接受百分比。

总体而言，在心理和生理舒适度的临时体验差距方面，FL中的许多子运动组合对主动与被动用户均表现出显著差异。主动用户的转向动作通常会导致各指标上的显著体验差距。值得注意的是，当主动用户转动且被动用户在WL和FL中转动头部时，

无论旋转轴是否相同（黄色背景）或不同（绿色背景），大多数指标均显示出显著间隔，超过半数的被动用户无法接受这些条件。有趣的是，当主动用户进行平移而被动用户头部朝相似方向转动时，这种操作缓解了存在感和运动感觉的间隔，甚至导致某些子运动组合出现负面体验间隔值（紫色背景）。

5.4 条件的可接受性与子运动组合

本节旨在根据可接受性结果筛选出部分条件及子运动组合：
包括对主动与被动用户均可接受的、对两者均不可接受的，以及对主动用户可接受但对被动用户不可接受的组合。未发现任何对主动用户不可接受却对被动用户可接受的案例。筛选规则如下：若主动与被动用户的可接受性均超过50%，则视为对两者均可接受；若两者可接受性均低于50%，则判定为对两者均不可接受；当主动用户可接受性超过50%而被动用户低于50%，且两者可接受性差异超过25%时，归类为对主动用户可接受但对被动用户不可接受。

根据图8(e)和(f)，主动与被动用户均可接受的条件为WS、WL和TS；
主动用户可接受但被动用户不可接受的条件包括FS、FL和TL。对于子运动组合，我们在表3中标注了双方均不可接受的（红色背景）、主动用户可接受但被动用户不可接受的（蓝色背景）情况。
主动用户而非被动用户（蓝色背景）在表3中，
且未标记的可接受性意味着两位用户都能接受。

5.5 不同速度或瞬移间隔组合的临时体验差距

本节旨在评估不同移动速度/传送间隔组合对临时体验差距的影响，并识别这些组合间的显著差异。

我们将运动节点分为6种组合类型：
高速/小间隔-静止站立、低速/大间隔-静止站立（WS、FS、TS中）；高速/小间隔-高转头速度、高速/小间隔-低转头速度、低速/大间隔-高转头速度、低速/大间隔-低转头速度（WL、FL、TL中）。

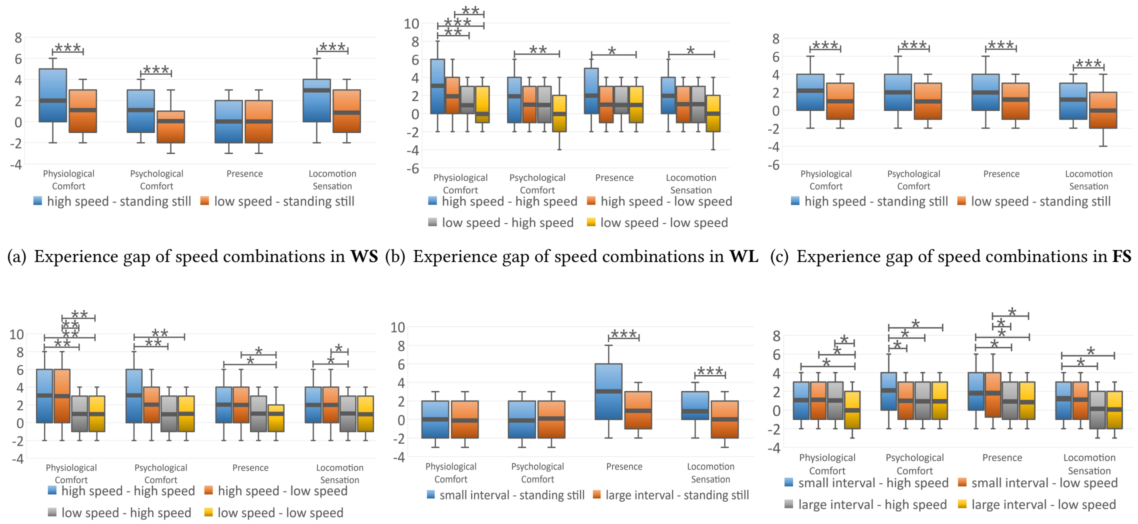
我们采用与5.3节相同的临时体验差距分数计算方法。
Wilcoxon符号秩检验结果显示：在WS中，高速-静止站立与低速-静止站立在生理舒适度（$Z = -13.292$, $p < .001$, $r = -.392$）、心理舒适度($Z = -10.376$, $p < .001$, $r = -.306$)及运动感觉（$Z = -13.583$, $p < .001$, $r = -.400$）上存在显著差异；在FS中，高速-静止站立与低速-静止站立在生理舒适度($Z = -13.508$, $p < .001$, $r = -.398$)上存在显著差异，

心理舒适度（$Z = -12.210$, $p < .001$, $r = -.359$）、存在感($Z = -9.531$, $p < .001$, $r = -.281$)及运动感觉($Z = -9.459$, $p < .001$, $r = -.279$); in TS方面，高速-静止站立与低速-静止站立在存在感($Z = -11.626$, $p < .001$, $r = -.343$)和运动感觉($Z = -10.732$, $p < .001$, $r = -.316$)上存在显著差异。Friedman检验结果显示，在WL中，4种行走速度-转头速度组合在生理舒适度（$\chi^2(3) = 30.016$, $p < .001$, $W = .532$）、心理舒适度（$\chi^2(3) = 22.086$, $p < .001$, $W = .451$）、存在感($\chi^2(3) = 16.315$, $p = .003$, $W = .325$)及运动感觉($\chi^2(3) = 26.076$, $p < .001$, $W = .463$)方面存在显著差异；在FL中，4种飞行速度-转头速度组合在生理舒适度（$\chi^2(3) = 42.384$, $p < .001$, $W = .478$）和心理舒适度($\chi^2(3) = 14.352$, $p = .004$, $W = .301$)方面存在显著差异，

存在感（$\chi^2(3) = 9.854$, $p = .011$, $W = .309$）与运动感觉($\chi^2(3) = 9.781$, $p = .012$, $W = .354$)；在TL中，4种瞬移间隔-头部转动速度组合在生理舒适度($\chi^2(3) = 9.994$, $p = .010$, $W = .469$)、心理舒适度($\chi^2(3) = 9.979$, $p = .011$, W方面存在显著差异 =
.464)、存在感($\chi^2(3) = 10.354$, $p = .010$, $W = .522$)与运动感觉($\chi^2(3) = 8.978$, $p = .022$, $W = .365$)。

临时体验差距数据的箱线图及
不同速度/间隔-转动头部
速度组合间通过配对比较显示的显著差异如图9(a)-(f)中，* 代表 p < .05，** 代表 p < .01，*** 代表 p < .001。

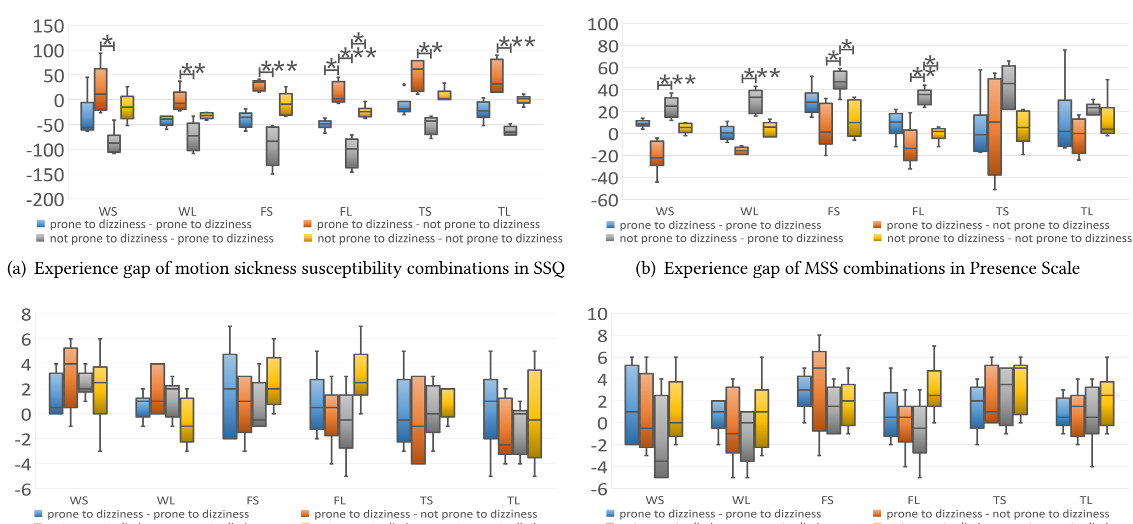
总体而言，高速/低间隔-静止站立在WS、FS和TS中具有最大的临时体验差距；高速/低间隔-高转头速度通常具有最大的临时体验差距，其次是WL、FL和TL中的高速/低间隔-低转头速度。



(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

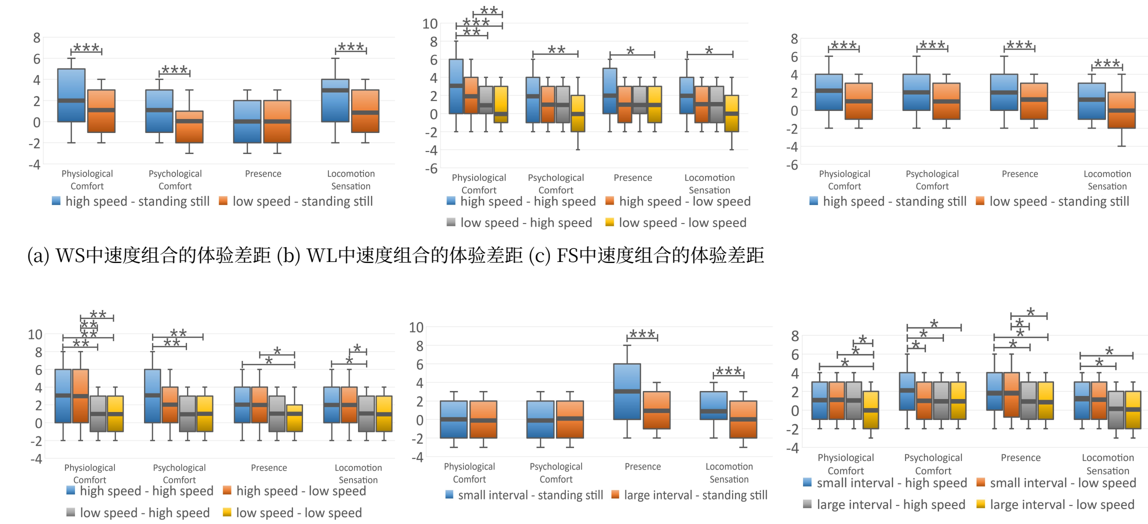
(c) Experience gap of MSS combinations in locomotion sensation (d) Experience gap of MSS combinations in psychological comfort

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.

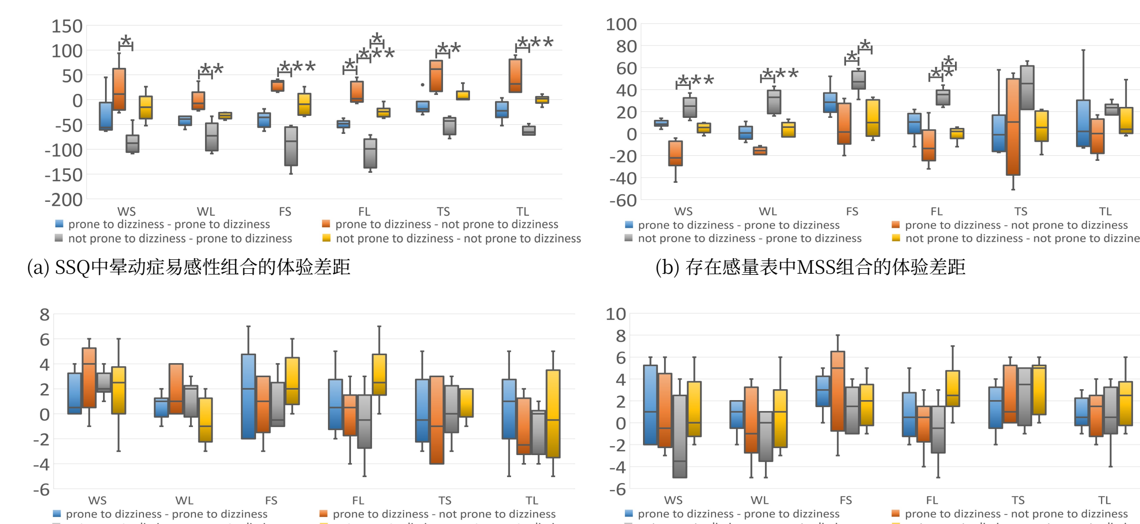
The calculating method of experience gap values was the same as in Section 5.2. The Friedman test results showed that for SSQ, there were significant differences between MSS combinations in **WS** ($\chi^2(3) = 9.000$, $p = .029$, $W = .500$), **WL** ($\chi^2(3) = 13.881$, $p = .003$, $W = .671$), **FS** ($\chi^2(3) = 17.746$, $p < .001$, $W = .593$), **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



(a) WS中速度组合的体验差距 (b) WL中速度组合的体验差距 (c) FS中速度组合的体验差距

(d) FL中速度组合的体验差距 (e) TS中间隔组合的体验差距 (f) TL中间隔组合的体验差距

图9：不同速度/瞬移间隔组合下主动与被动用户间的临时体验差距



(a) SSQ中晕动症易感性组合的体验差距 (b) 存在感量表中MSS组合的体验差距

(c) 移动感觉中MSS组合的体验差距 (d) 心理舒适度中MSS组合的体验差距

图10: 后测问卷中不同晕动症易感性组合的体验差距

5.6 不同MSS组合的体验差距

根据4.1节中的4种MSS组合，本节旨在研究MSS组合对体验差距的影响，以及不同MSS组合之间的显著差异。

一方面，值得探究MSS是否会对除易预测的SSQ之外的指标体验差距产生影响。另一方面，尽管不易头晕——易眩晕可能很容易被预测为导致最大的运动病差距，但了解其他指标的差距排名也颇具意义。

MSS组合。

体验差距数值的计算方法与第5.2节相同。弗里德曼检验结果显示，对于SSQ，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（$\chi^2(3) = 15.001$, $p = .002$, $W = .533$）和TL（$\chi^2(3) = 17.746$, $p < .001$, $W = .686$）的MSS组合之间存在显著差异；对于存在感量表，MSS组合之间也存在显著差异

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.

WS（$\chi^2(3) = 17.586$, $p < .001$, $W = .677$）、WL（$\chi^2(3) = 17.024$, $p = .001$, $W = .544$）、FS（$\chi^2(3) = 11.800$, $p = .008$, $W = .656$）和FL（$\chi^2(3) = 14.005$, $p = .003$, $W = .778$）的MSS组合之间存在显著差异。

经验差距数据的箱线图及通过配对比较显示的不同MSS组合间的显著差异如图10(a)-(d)所示，其中*代表p < .05，**代表p < .01，***代表p < .001。

总体而言，不易头晕-易眩晕组在
模拟器疾病问卷和存在感量表中的体验差距最大，其次是
易眩晕-易眩晕组，以及易眩晕-不易头晕组
导致头晕的体验差距最小。有趣的是，MSS
组合对运动感觉没有显著影响
和心理舒适度。

6 讨论

本研究是探索性的，在实验前缺乏预先制定的假设。
因此，本节中的所有讨论均呈现
探索性见解 [106]。

6.1 条件对体验的影响 后测问卷中的差距

在WS和WL条件下，主动用户通过视觉、前庭和行走时的本体感觉刺激协调一致，以最小的感觉运动冲突体验自然的运动感觉。

而在WS中，被动用户仅接收视觉刺激；在WL中，被动用户环顾四周会进一步导致视觉与其他感官对运动方向的感知不匹配。

这导致主动与被动用户在这些条件下的晕动症差异显著。但令人惊讶的是，这些感官冲突并未造成WS和WL中主动与被动用户在存在感上的显著差异。参与者反馈表明，主动用户交替步伐引起的左右摇晃和轻微抖动视图为被动用户营造了行走错觉，使其产生正在行走的感受。该效果在WL中更为明显，从而消除了主动与被动用户在运动感觉上的显著差异。

FS与斯托夫雷根的基于驾驶的共同运动研究[16, 21], 设置及部分结果相符——在此条件下，主动与被动用户仅存在移动意图和微弱本体感觉刺激（即推动操纵杆）的差异，从而验证了"驾驶员-乘客效应"并再次突显了移动意图的关键作用。不同的是，我们的研究引入了更高的运动自由度，运动节点中有更多轴进行移动和旋转，尤其在FL中，被动用户还会转动头部。这深化了研究结果，并提供了其研究中未涉及的新见解。转向相关运动节点的普遍性使得FS和FL在多项指标上相较其他条件表现出显著差异。飞行高度的变化（尤其是FL中）可能引发缺乏运动控制的被动用户产生心理不适，导致恐惧与兴奋的感受。

在FL中，参与者报告了类似乘坐过山车观赏周围景色的体验，既感到兴奋又出现头晕症状。

相反，很少有主动用户报告这种感觉，他们的反馈大多认为控制飞行很有趣。这可能解释了在生理与心理舒适度方面存在的显著间隔，

FS和FL中，存在感和移动方面没有显著间隔
FL中主动用户与被动用户之间的感受差异。

TS和TL中的主动用户表示，他们能根据引导对象更好地把握传输时机，且此类移动几乎不会引发头晕。TS中的被动参与者反馈称，他们感觉像是在观看PPT或动态图片集，这种陌生感削弱了其存在感。而在TL中，许多被动参与者报告称，由于观察场景时突然的瞬移干扰了获取所需场景信息，导致空间感知下降和迷失感增强，因而对这种移动方式感到不适。这造成TL中主动与被动用户在存在感和心理舒适度上存在显著差异，同时TL与TS之间也存在较大的可接受性差距。

6.2 子移动类型对 临时体验差距的影响

主动与被动用户之间在临时移动体验上存在显著差异，
尤其在主动用户操作时更为明显。
转动。在WL和FL中，当主动用户的旋转轴与
被动用户的头部转动轴对齐时，会出现极大的体验
差距（例如表3中的黄色部分）。这是由于被动
用户在视觉上感知到速度加倍或相互抵消，
具体取决于主动与被动用户转动方向相同或相反，类似于应用动态视觉重定向技术时

的旋转增益，即改变物理动作与
对应的虚拟响应[42, 71], 会导致突然的视觉

速度变化，正如参与者报告的头部转动方向改变时
所描述。此外，当主动与被动用户
沿不同旋转轴转动时（即表3中的绿色背景区域），会出现显著的体验差距。我们推测这是由于被动用户

在视觉上感知到双旋转轴的复合运动，与前庭觉仅感知到单轴旋转产生冲突

从而引发感觉运动冲突和潜在的伪科里奥利效应
加剧晕动症[23, 49, 50]的效应。

此外，在某些运动节点（如主动用户平移而被动用户朝相似方向转头的场景，参见表3紫色部分），主动与被动用户在存在感和运动感觉上存在微小间隔。部分被动用户的评分甚至超过主动用户，并报告了强烈的运动感觉——尽管仅转动头部却仿佛真实移动。这种现象可能归因于转头动作包含颈部为中心的头部回转（即在旋转基础上还存在弧形平移），尤其是上下环视动作；当主动用户平移与被动用户转头方向相似时（例如主动用户前移/上移/下移与被动用户上下转头），会混淆被动用户大脑对视觉和前庭信号的判断，误以为二者一致从而产生平移错觉。该特性被应用于部分虚拟现实中的具身运动方法（如通过头部或躯干旋转/倾斜控制平移的头部操纵杆[41], 和身体倾斜[31, 41, 104], ），这些方法被证实能有效产生卓越的运动感觉。

此外，在FS和FL中，主动用户的滚动旋转会显著影响他们自身及被动用户的生理不适。

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.

这可能归因于日常生活中滚动旋转的罕见性；主动用户的上下平移也会影响心理舒适度的间隔。部分被动用户报告称感到惊吓或不安，尤其是在突然上升或下降时。在TS和TL中，瞬移会打断被动用户的持续观察，导致心理舒适度和存在感出现显著差异；主动用户因离散瞬移产生的运动感觉不如被动用户转头诱发的运动感觉强烈，从而在运动感觉上产生一些负面间隔。

6.3 速度/瞬移间隔与MSS对体验差距的影响

总体而言，移动/转头速度与瞬移 -
间隔对许多临时体验差距的影响是显而易见的。高速/小间隔-静止站立产生的差距大于WS、FS和TS中高速/小间隔-静止站立的情况，这很容易理解，因为更强的视觉刺激会进一步加剧感觉冲突水平，特别是对于没有移动意图、前庭和本体感觉刺激的被动用户。另一方面，高速/小间隔-高转头速度与低速/大间隔-低转头速度分别在WL、FL和TL中产生最大和最小的体验差距，这也很好理解，因为被动用户比静止站立时更容易四处张望，从而进一步加剧感觉运动冲突。有趣的是，高速/小间隔-低转头速度在某些指标上的体验差距通常大于低速/大间隔-高转头速度，这表明在协同移动中，主动用户的运动参数对体验差距的影响比被动用户的运动参数更重要。

此外，作为已知显著影响晕动症程度的因素，MSS不仅对晕动症差距有显著影响，还对存在感差距产生显著作用，这表明晕动症的强度也会影响存在感差距。其中，不易头晕者与易眩晕者之间的体验差距通常最大，这一点易于理解。

有趣的是，对于其他3种MSS组合，易眩晕者与不易头晕者之间的体验差距通常最小，而易眩晕者之间及不易头晕者之间的体验差距则无显著差异。这些排序结果为实际协同移动情境中主动与被动用户的配对/组合提供了参考。此外，MSS对运动感觉和心理舒适度无影响表明，仅凭晕动症的显著差距不足以导致共同运动场景中这两项指标的体验差距。

6.4 研究价值与启示

本研究所选条件与子运动组合具有代表性，涵盖三类感官对齐的具身运动方法（行走）、采用驾驶隐喻与本体感受刺激的移动方法（飞行摇杆）及离散运动（瞬移），以及被动用户的两种常见交互行为。值得注意的是，除运动意图外，研究重点关注由

感觉运动冲突引发的体验差距，这种现象在协同移动场景中普遍存在。可以合理预期，本文的研究成果可应用于更多实际协同移动场景中的协作任务。对于某些动态共同运动场景，例如在激烈多人游戏中，主动用户驾驶车辆躲避敌人追击而被动用户负责攻击敌人时，主动与被动用户之间难以沟通运动意图——这与本文实验设置相似，因此研究成果可直接为保障体验提供参考。对于允许运动意图沟通的场景（如主动用户引路而被动用户执行任务），本研究关于感觉运动冲突相关条件/子移动组合的结论（例如，

涉及被动用户环顾四周的协同移动）同样具有重要参考价值。

具体而言，探索虚拟现实共同运动中主动与
被动用户之间的体验差距，具有以下研究价值
与启示：
首先，基于可接受性及其他体验维度的差距，
每种条件及条件间的指标（第
5.1和5.2节），设计师可以了解各
种共同运动条件的优势与不足，以及条件
排名。这一洞见有助于识别哪些条件能提供
更优的体验，可直接应用于共同运动
场景，而哪些条件需要进一步改进以实现高效
应用。
其次，作为其他研究中鲜少探讨的体验维度，
临时体验的积累将为整个移动
条件的整体体验奠定基础。设计多样的子运动组合
能帮助我们细致理解哪些组合可能产生
特定效果。
显著的临时体验差距（第5.3节）。这一认识使设计师能够有意识地避免或干预

在设计协同移动时，这些子运动组合
场景，例如设置景观或生成动态元素，如行人、动物等，以吸引注意力

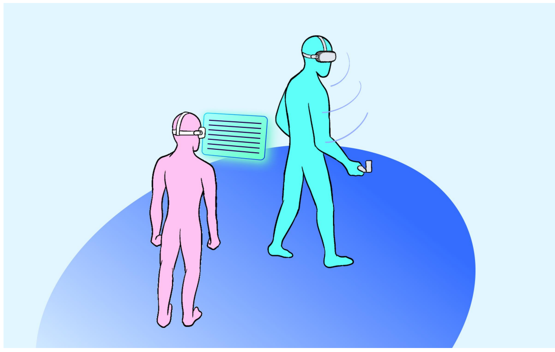
无论是主动用户还是被动用户，从而减少用户行为

导致显著的体验差距。同时，它有助于识别
在这些场景中可以放心使用的组合。
第三，运动参数组合的评估结果可作为设定速度/瞬移间隔的依据

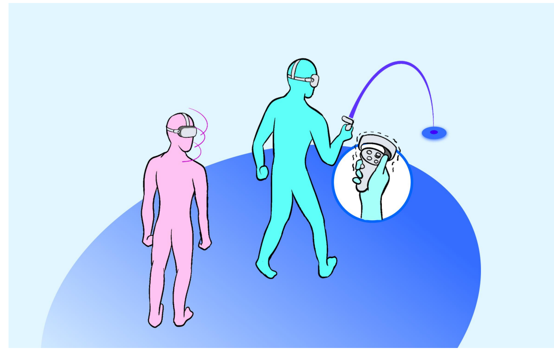
在协同移动场景中。例如，优先考虑对
主动用户进行参数合理调整，因为其在体验差距中起主导作用。MSS组合的评估结果

可指导主动与被动用户的配对。
例如，优先将易眩晕者设为主动
用户，不易头晕者设为被动用户
有助于缩小体验差距。在此背景下，尽管
主动用户可能更容易出现头晕症状，但他们拥有
对运动的控制权，可随时调整以缓解
其生理不适。
第四，本研究对共同运动场景中多种体验差距成因的推测，
有助于更深入理解人类感知系统如何响应不同协同移动场景。

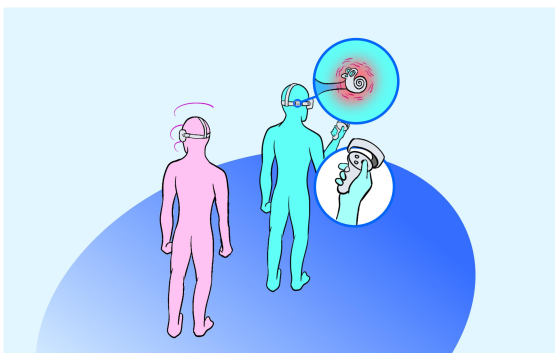
这也有助于揭示虚拟协同移动环境中感官刺激与用户体验之间复杂的关系。



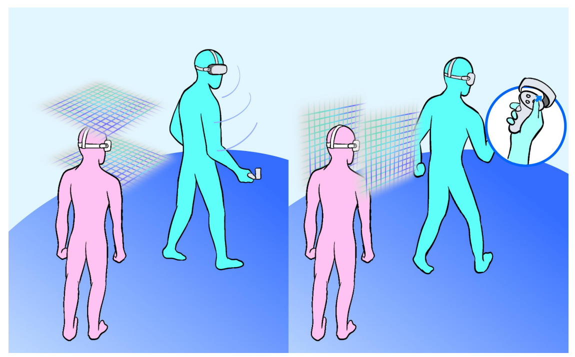
(a) Visual text reminder to the passive user



(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.

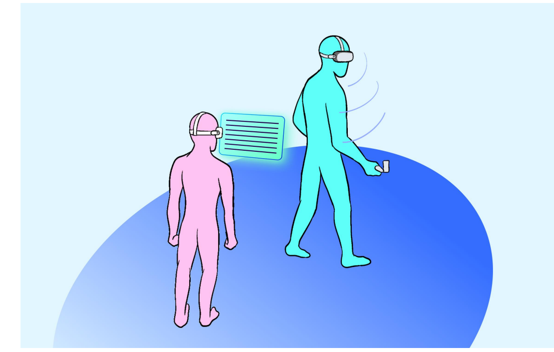
6.5 Limitations and Future Work

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.

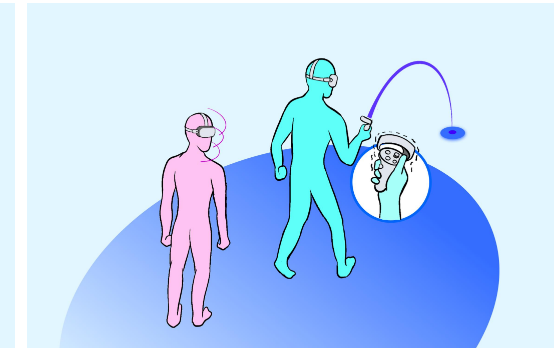
To measure temporary experiences, we set locomotion nodes by combining possible sub-locomotion and speed/interval parameters for each condition. Although we balance the settings of locomotion nodes for each condition in terms of quantity, duration, and sequence to simulate actual co-locomotion scenarios 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.

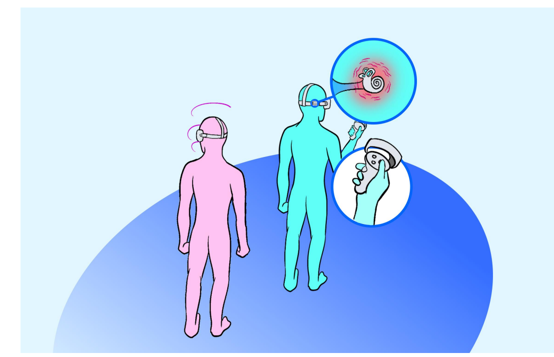
In the future, we will further explore feasible automated sensory intervention methods based on the results of this paper in co-locomotion scenarios. For example, when the active user turns body, the application system automatically provides a visual text



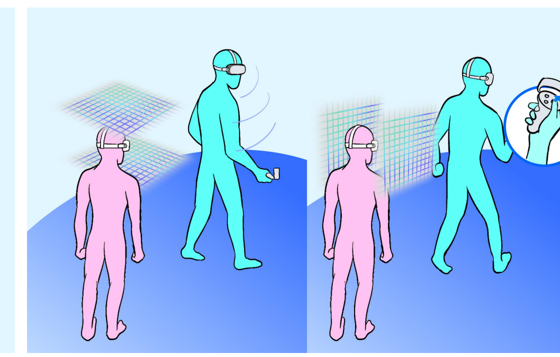
(a) 向被动用户展示视觉文本提醒



(b) 对主动用户手柄施加振动



(c) 通过前庭电刺激将被动用户的前庭感觉传递给主动用户



(d) 对被动用户施加视觉障碍以限制其环顾四周

图11：基于子运动组合中临时体验差距的动态干预方法

最后，大多数参与者的反馈表明，条件或子运动可接受性的主要决定因素是生理舒适度，其次是心理舒适度，然后是存在感，最后是运动感觉。因此，我们建议在设计共同运动场景时优先考虑可接受性差距，因为它提供了对条件/运动节点体验的全面感受。随后，应考虑生理舒适度差距、心理舒适度差距、存在感差距，

以及运动感觉差距。这为开发涉及协同移动的应用程序提供了宝贵的指导，帮助他们应对挑战并创建更具包容性和令人满意的虚拟现实应用。

6.5 局限性与未来工作

尽管我们的研究采用了平衡的条件序列，并在条件间提供了相对充足的休息时间，但如同许多其他受试者内设计一样，可能仍无法完全消除晕动症的遗留效应。一些初步研究表明，晕动症有时可能表现出延迟发作，参与者某一时刻感觉良好，但随后症状会加重[103]。考虑到目前缺乏科学证据证明晕动症可能具有长期性及其对遗留效应发展的影响（例如，线性与否），这些不明确的影响可能在一定程度上限制本文讨论的晕动症结果的可靠性。未来，我们将进一步从研究结果中筛选出值得注意或有趣的条件与运动节点，并采用更可靠的方法来消除条件间的遗留效应，例如在不同条件间设置超过24小时的间隔，以进一步验证我们的结果及推测的潜在原因。

为了测量临时体验，我们通过
结合可能的子运动和速度/间隔参数
为每种条件设置运动节点。尽管我们在数量、持续时间和

序列尽可能真实地模拟实际共同运动场景
但仍可能对条件间的可比性产生一定影响
。

类似斯托夫雷根研究[15,的实验策略
16, 21], 我们的研究分别评估主动与被动用户
以模拟协同移动同时最小化协作互动
之间。这种方法可能会在一定程度上影响研究结果的普适性。未来，我们将进一步研究

共同运动场景中协作任务与交流意图的体验差距,
任务与交流意图。

未来，我们将基于本文成果在共同运动场景中进一步探索可行的自动化感官干预方法,

例如当主动用户转动时
正文中，应用系统会自动向被动用户提供可视化文本

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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提醒以避免环顾四周（图11(a)）；当被动用户环顾四周时，系统会向主动用户手柄施加振动以阻止其瞬移（图11(b)）；对主动用户施加动态前庭电刺激（GVS）使其前庭感觉与被动用户趋同，从而更及时地调整移动行为，如移动速度、速度变化频率和休息时间（图11(c)）；当主动用户旋转时，会在被动用户头部上下或左右两侧生成视觉障碍，使其即使转头也无法观察周边环境，从而放弃转头意图（图11(d)）。这些干预措施的强度可基于本文提出的子运动组合临时体验差距结果值进行调整。

7 结论

综上所述，我们的研究深入探讨了多用户协同移动中主动与被动用户之间的体验差距，特别关注子运动组合的临时体验差距。通过全面分析主动用户移动方法、被动用户行为、子运动、速度/间隔及MSS的各种组合，我们识别出不同条件和子运动组合中存在显著的体验差距，揭示了影响用户体验的关键情境。总体而言，被动用户比主动用户更容易感受到明显的舒适度下降，尤其是在涉及被动用户环顾四周的条件下。有趣的是，当主动用户转动而被动用户观察环境时，子运动组合中的感官冲突差距尤为突出；当主动用户平移与被动用户头部旋转方向一致时，会增强被动用户的存在感和运动感觉，这表明人类对感觉运动冲突存在复杂的应对机制。这些发现强调了考虑移动条件、子运动类型与参数以及个体差异对提升协同移动体验的重要性。

最后，我们的分析涵盖了研究结果的潜在原因、数值和灵感，揭示了协同移动中的微妙洞见。

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