Effects of Third-Person Locomotion Techniques on Sense of Embodiment in Virtual Reality

Johanna Ulrichs
Department of Computer and Systems Sciences (DSV)
Stockholm University
Stockholm, Sweden
joul4614@student.su.se

Andrii Matviienko
Department of Media Technology and Interaction Design (MID)
KTH Royal Institute of Technology
Stockholm, Sweden
andriim@kth.se

Luis Quintero
Department of Computer and Systems Sciences (DSV)
Stockholm University
Stockholm, Sweden
luis.quintero@dsv.su.se

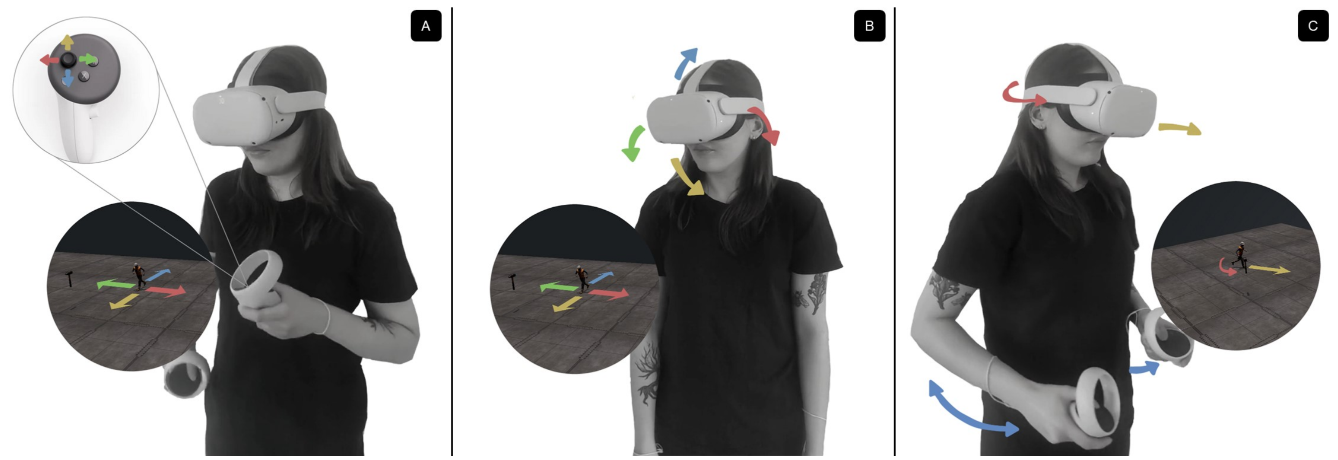

Figure 1: Three third-person VR locomotion techniques explored in the paper and sorted in an incremental level of bodily engagement: (A) *controller joystick* that employs a controller's joystick to move an avatar in all directions, (B) *head tilt* that utilizes users' head movement to navigate an avatar in all directions, and (C) *arm swing* that uses users' hand swing to facilitate avatar movement in the direction indicated via a head rotation.

Abstract

Virtual Reality (VR) has enabled novel ways to study embodiment and understand how a virtual avatar may be treated as part of a person's body. These studies mainly employ virtual bodies perceived from a first-person perspective, given that VR has a default egocentric view. Third-person perspective (3PP) within VR has positively influenced the navigation time and spatial orientation in large virtual worlds. However, the relationship between VR locomotion in 3PP and the sense of embodiment in the users remains unexplored. In this paper, we proposed three VR locomotion techniques in 3PP (controller joystick, head tilt, arm swing). We evaluated them in a user study (N=16) focusing on their influence on the sense of embodiment, perceived usability, VR sickness, and completion time. Our results showed that arm swing and head tilt facilitate higher embodiment than a controller joystick but lead to higher completion times and oculomotor sickness.

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CCS Concepts

• **Human-centered computing → Virtual reality**; *Empirical studies in HCI*.

Keywords

Virtual Reality, Locomotion, Embodiment, User Experience, Third-Person Perspective, VR, UX, 3PP

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1 Introduction

Virtual Reality (VR) technology inherently offers the sensation of being the protagonist in a virtual experience. Adding a virtual body or avatar in VR has proved to enhance body transfer illusions [47], spatial presence [17], and sense of embodiment (SoE) [16, 26]. Researchers have studied psychological elements of embodiment for a long time, interested in how an external object can be treated as part of a person's own body [30, 49]. A famous example that artificially induced SoE through multisensory stimulation with a fake object is the rubber hand illusion [5] or virtual hand modifications [44, 45]. Similarly, VR has also become a ubiquitous tool that allows unique experimental manipulations to understand what it feels to own, control, and be inside a virtual avatar [3, 19, 26]. Some of the factors known to affect SoE in VR are visuomotor synchrony between the user and avatar [31, 39] and the avatar's realism [20, 29]. However, the influence of viewpoints, i.e., first-person perspective (1PP) and third-person perspective (3PP), on embodiment has varying conclusions [10, 23, 41, 47]. Therefore, there still needs to be a greater understanding of whether 3PP in VR may influence the perceived embodiment of virtual avatars.

Due to default 1PP of VR, most of the proposed locomotion techniques have focused on the prevalent egocentric view [1, 4, 11]. Several taxonomies categorized more than a hundred locomotion implementations into three main ways to move in VR worlds: teleportation, physical movement, and steering methods. The few researchers who explored VR locomotion in 3PP have proposed hybrid embodied methods that switch between 1PP and 3PP [7, 18, 42]. The transition between viewpoints in VR resulted in benefits for navigation of large environments, spatial orientation, and reduced motion sickness. Nevertheless, the relationship between VR locomotion and embodiment strictly in 3PP remains unclear, and elucidating such a connection could expand the range of self-representation in virtual environments [16].

In this paper, we explore the influence of the third-person locomotion techniques on the sense of embodiment. For this, we developed three third-person locomotion techniques with different physical engagement levels: (1) *controller joystick* that employs a controller's joystick to move an avatar in all directions, (2) *head tilt* that utilizes users' head movement to navigate an avatar in all directions, and (3) *arm swing* that uses users' hand swing to facilitate avatar movement in the direction indicated via a head rotation (Figure 1). To explore the influence of these methods on the sense of embodiment, we conducted a controlled lab experiment (N=16), in which participants had to manipulate a VR avatar in a third-person perspective. We found that head tilt and arm swing elicit a higher sense of embodiment. However, they may increase the time to complete a task and the oculomotor sickness compared to the controller joystick.

The main **contributions** of our work are: Three techniques for VR locomotion in third-person perspective and an empirical evaluation of three third-person VR locomotion techniques focused on the sense of embodiment, perceived usability, and VR sickness.

2 Related Work

This section outlines the foundational topics to explore the effect of VR locomotion in a third-person perspective (3PP) on the user's perceived sense of embodiment (SoE).

2.1 Sense of Embodiment with Virtual Objects

SoE refers to an ensemble of sensations that emerge when an object's properties are processed as if they were our own biological body [49]. Despite the several definitions of embodiment [30], SoE is the widely adopted construct in VR research, with humanoid virtual avatars as the most commonly visualized artificial object [26]. SoE has three conceptual dimensions: sense of body ownership (SBO), sense of agency (SA), and sense of self-location (SSL). However, a meta-analysis found that many VR studies used the terms embodiment and body ownership interchangeably, omitting the components of agency and self-location [39]. SBO refers to the feeling that the body is the source of sensations. A typical example of high SBO is the rubber-hand illusion [5], demonstrating that body ownership may arise from virtual arms under synchronous visuotactile feedback. Research has also found that SBO can arise from full-bodied virtual avatars [47] and be affected by the avatar's size [16]. SA refers to bodily obedience [9], or the feeling of being the cause of action. An object is embodied if a person feels that it obeys their will. High SA can be elicited through synchronous visuomotor stimulation, and their psychological effects have been used for phantom limb pain rehabilitation [8]. SSL is the volume in space where a person experiences to be placed. An out-of-body experience can be generated in cases where the perceived self-location and the body space are not collocated, and the users perceive themselves outside their physical body [2]. SSL is greatly affected by visuospatial perspective [19], i.e., 1PP and 3PP, with numerous research indicating that SSL is higher when the visuospatial perspective is egocentric. For instance, heart rate response to a physical threat given to the virtual body was higher in 1PP than in 3PP [47]. In addition, SSL is influenced by vestibular signals involving bodily movements such as rotation, translation, and orientation about gravity, which can create sensations of out-of-body experience [2].

The three dimensions of SoE are not independent. Previous work has found that SBO and SSL are strongly coupled [19]. For example, manipulating SSL to create a 3PP, where there is no overlap between the user and the virtual body, does not preserve the SBO [34]. However, the relationship between SA and SBO is uncertain; for example, avatar realism has been shown to increase SBO but has varying effects on SA [19].

2.2 Virtual Reality Locomotion

More than a hundred VR locomotion techniques have been reported in academic publications or implemented in commercial videogames [11]. The current prevalent techniques to provide users with the ability to move and explore virtual environments are the point-and-teleport, movement (e.g., arm swinging or walking-in-place), and steering methods (e.g., controller joysticks or head directed) [1, 4, 33, 35]. A prominent research line has focused on creating taxonomies to categorize locomotion techniques [1], including computational algorithms for clustering [33]. Other studies experimentally evaluate novel locomotion implementations against existing methods [6, 28]. Since VR is predominantly experienced in first-person view, most research also concentrates on locomotion techniques from an egocentric perspective. Few novel interactions have tried to replicate computer-based locomotion into VR experiences, such as a tile-based technique proper for real-size VR board games [13, 46] or optical-illusion-based locomotion that employs the same pinch interaction to resize 2D pictures as a way to move in 3D worlds. However, embodied locomotion has also been studied in the context of 3PP [52] and perspective continuum [23]. For example, 3PP-R [12] enabled natural movement through a world-in-miniature that orbits around the user as they rotate, and this method induced less simulation sickness than 1PP but also lower

SA. Moreover, hybrid approaches let users switch between 1PP and 3PP. One implementation, called out-of-body locomotion, showed higher efficiency than teleportation [18] and another project using bird's eye perspective allowed faster navigation of large-scale virtual environments with increased spatial orientation and less motion sickness [7]. Prithul *et al.* presented a solution that enables 3PP VR locomotion through head tilting and full-body tracking with a depth camera, which yielded more SoE than controller-based locomotion across all dimensions [42]. Therefore, in this paper, we focus on investigating locomotion and embodiment entirely within a 3PP context. Our work compares two steering-based locomotion techniques, i.e., controller joystick and head tilt, and one movement-based technique, i.e., arm swing. Only a few comparative studies in 3PP VR have involved one movement-based technique and either one steering- or teleportation-based technique. This choice enables the examination of the influence of locomotion technique on embodiment, excluding the well-known influence of 1PP on embodiment and allowing a nuanced comparison of locomotion methods with different levels of bodily activity.

3 Evaluation

With this work, we contribute to the discourse on novel VR locomotion methods beyond traditional egocentric perspectives. Therefore, we focus on the following research question: **How do locomotion techniques based on head tilting, arm swinging, and controller joystick input affect the user experience and sense of embodiment in third-person perspective VR?**. To answer this research question, we conducted a controlled lab experiment to systematically investigate the performance of the methods and their influence on the sense of embodiment, which we outline in detail in the following.

3.1 Participants

We recruited a total of 16 participants via university communication channels (9 identified as male, 6 female, and 1 non-binary), aged between 21 and 42 years old ($M = 28$, $SD = 6.35$). All participants had previous experience in VR, and 14 used it often for work, studies, or recreational purposes. A total of 12 participants regularly played PC or console games during the last six months, 9 of them playing weekly or daily. The inclusion criteria were to not suffer from any preexisting medical conditions outlined in the Meta Quest Health and Safety Guidelines [38]. All participants had normal or corrected-to-normal vision.

3.2 Study Design

The experiment followed a within-subjects approach; participants used three VR locomotion techniques to control an avatar from a third-person view. The order of the three conditions was counterbalanced to mitigate potential bias, influence of fatigue, and learnability. The study outlined *VR locomotion technique in 3PP* as the only independent variable with three different levels (Figure 1):

3.2.1 Controller Joystick: This condition acted as a control condition to provide a baseline measure. The user used the left controller's joystick to move in all directions, following the locomotion conventions for most console games (Figure 1-A). The player needed to view the game in the HMD and move the avatar using the joystick, contributing to its similarity to traditional console games, with the addition of being able to look around in the virtual world using the HMD.

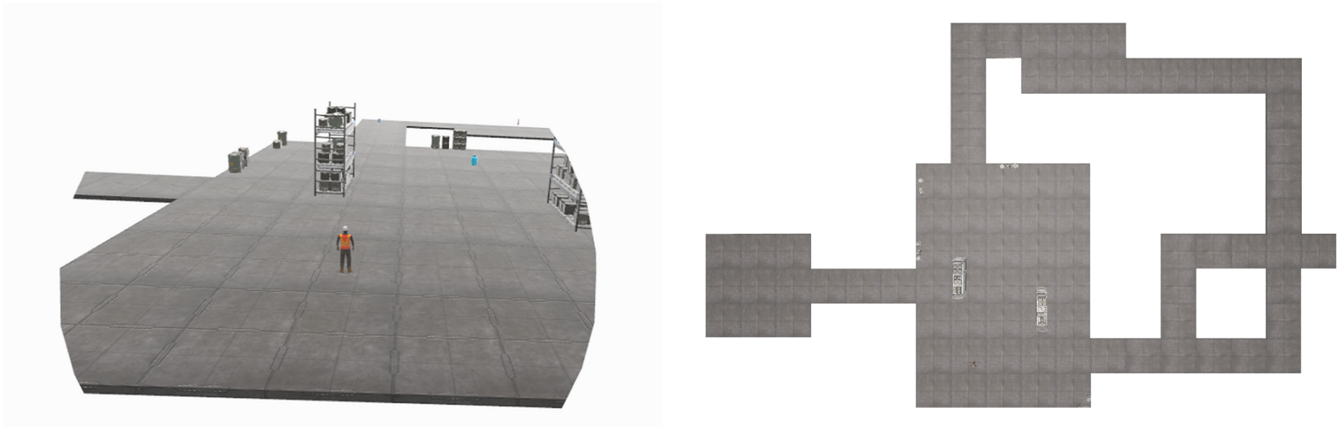
3.2.2 Head Tilt: The head tilt locomotion technique utilized as input the rotation of the headset on different axes to move the virtual avatar, enabling the player to tilt their head in order to move in the virtual environment (Figure 1-B), based on the previous work that employs head rotations for steering [21, 36]. The rotation around the headset's x-axis (roll) determined the avatar's horizontal movement (left-right). The angle around the y-axis (pitch) controlled the direction the avatar moved vertically (forward-backwards). Furthermore, the player can combine these two inputs to move diagonally, for instance, by tilting their head slightly down and to the right to move forward at a 45° angle towards the right. The avatar movement was activated when the angle of the headset exceeded a predefined threshold of 20 degrees and was canceled when the headset was in an upright position.

3.2.3 Arm Swing: In this locomotion technique, players move forward by swinging their arms back and forth while pressing the trigger button on both controllers, based on the previous work that employed body rotations for steering in jogging-in-place [22]. In order to change the moving direction, the virtual avatar rotated concurrently with the headset's yaw rotation (around the z-axis), resulting in the avatar and the player always facing the same direction. Additionally, the game view rotates along with the player and keeps the avatar always in front of the player (Figure 1-C).

These three inputs for locomotion were selected as they possess varying levels of physicality or bodily engagement, ranging from minimal bodily engagement, i.e., steering a joystick using thumb movements, to high bodily engagement, i.e., arm swinging and turning the body. A high level of bodily engagement has been shown to be correlated with reduced motion sickness in 1PP VR experiences [43]. Moreover, body movement has been a promising indicator of overall user engagement in VR gaming [48].

3.3 Task

The task consisted of a mini-game assessing the three locomotion techniques. In the mini-game, the player assumes the role of a construction worker in a warehouse (Figure 2a). The objective of the game is to navigate and explore the warehouse to collect ten tools floating above the floor, placed in a way so that the player needs to explore the entirety of the warehouse to complete the task (Figure 2b). The virtual avatar has a predefined animated run-cycle, which triggers when the avatar moves in any direction. The avatar's movement speed was set to 4 units/s across all three locomotion techniques and is constant for the entire duration of the game, regardless of variations in the user input controlling the locomotion. For instance, swinging the arms with a higher velocity would not affect the speed of the avatar. Similarly, the angle of the head tilt or the axis value of the joystick did not have any effect on the speed of the avatar. The layout of the game map remained the same in all three conditions, but the tools were spawned in different positions per game mode. As the avatar moves, the game camera follows it. The camera providing 3PP was positioned 20 units behind and 8 units above the avatar. This distance is intended to reduce



(a) View within the virtual environment, showing the avatar and the game map with a limited field-of-view to reduce motion sickness

(b) Top-down view of the game map the avatar must traverse to complete the game

Figure 2: Setup of the VR mini-game used to control the avatar in third-person perspective.

motion sickness due to the camera's movement. Moreover, the game environment is shown in a circular orb shape (Figure 2a) to limit the player's field-of-view and minimize VR sickness.

3.4 Apparatus

The task was developed in the Unity game engine v.2022.3.18 and deployed on VR HMD Meta Quest 2. The experimental area for the study was configured as a space of 3m x 3m to guarantee a safe space for VR locomotion.

3.5 Data Collection

To compare the three VR locomotion techniques in 3PP, we measured the following dependent variables:

- **Sense of Embodiment:** This paper uses the definition of embodiment related to the SoE originally outlined by Kilteni *et al.* [26]. The items comprising the questionnaire capture primarily SSL, SA, and SBO within a virtual environment. Therefore, this study uses the questionnaire suggested by Gonzalez-Franco and Peck [15], as it agrees with the classification of SoE. The original questionnaire was modified by omitting the subsets that were irrelevant to this study (i.e., tactile sensations, external appearance, and response to external stimuli) and the two individual items concerning SBO in mirror reflections, which did not apply in the current study. The resulting questionnaire consists of 10 items based on the three dimensions of SoE; participants express their agreement with each item on a 7-point Likert scale, spanning from -3 (strongly disagree) to 3 (strongly agree).
- **Perceived Usability:** In this paper, perceived usability refers to the ease and naturalness of the locomotion system. We employed the questionnaire introduced by McMahan *et al.* [37], as it is considered highly relevant for measuring the perceived usability of VR interactions. Adjustments in the statements were made to suit the topic of the VR mini-game. The questionnaire consists of 12 items related to VR usability, each assessed using a 7-point Likert scale, with higher values representing better usability (i.e., more easiness, more naturalness, more fun, and less exhaustion).
- **Virtual Reality Sickness:** As an essential factor of overall user experience, potential VR simulator sickness was assessed after each condition using the Virtual Reality Sickness Questionnaire (VRSQ) proposed by Kim *et al.* [27]. The questionnaire is based on the Simulator Sickness Questionnaire [24] focusing on characteristics of simulator sickness observed within VR environments. The selected items include Oculomotor (four symptoms) and Disorientation (five symptoms) measured through a 4-point Likert scale, where each point represents a level of experienced severity.
- **Completion time (in seconds):** For each condition, the completion time for each game mode is recorded to complement the questionnaire data. The time limit for a trial was set to 10 minutes.
- **Post-experiment discussion:** After the study, participants were briefly asked to assess their preferences and insights into the experience, enhancing the interpretation of the quantitative analysis.

3.6 Procedure

The procedure began with an introductory stage where the participant read the study's consent form, asked questions, and signed it. The participant was invited to the experimental area and briefly introduced to VR technology and the study's aim. Subsequently, we started the experiment by asking participants to fill out the demographics questionnaire. Then, the first play session was initiated, where the participant played one version of the VR mini-game either until it was finished or 10 minutes had passed. Each play session started with a calibration stage to guarantee that the user's starting position was aligned with the virtual world's front direction. The completion time for each version was recorded. After the play session, the participants completed the questionnaires targeting embodiment, usability, and VR sickness. This procedure was

Table 1: Results of pairwise comparisons between VR locomotion techniques (*CJ: Controller-Joystick; HT: Head Tilt; AS: Arm Swing*). The table shows common language effect sizes (CLES) and p-values for each dependent variable (*SoE: Sense of Embodiment; VRS: VR Sickness*).

	VR Locomotion	HT vs. CJ	AS vs. CJ	AS vs. HT
	Measurement	*CLES (p)*	*CLES (p)*	*CLES(p)*
SoE	*Body Ownership*	0.775 (<0.001)	0.867 (0.002)	0.594 (0.773)
	Agency	0.781 (0.005)	0.895 (<0.001)	0.709 (0.016)
	Self-Location	0.594 (0.029)	0.695 (0.040)	0.562 (0.621)
	Total	0.834 (<0.001)	0.932 (<0.001)	0.684 (0.028)
Usability	*Easiness*	0.148 (<0.001)	0.340 (0.094)	0.656 (0.065)
	Naturalness	0.217 (<0.001)	0.385 (0.132)	0.656 (0.009)
	Fun	0.426 (0.233)	0.576 (0.305)	0.635 (0.048)
	Exhaustion	0.297 (0.014)	0.383 (0.090)	0.559 (0.394)
	Total	0.174 (<0.001)	0.354 (0.078)	0.686 (0.026)
VRS	*Oculomotor*	0.777 (0.003)	0.734 (0.028)	0.488 (0.789)
	Disorientation	0.617 (0.192)	0.668 (0.068)	0.533 (0.905)
	Total	0.803 (0.005)	0.762 (0.014)	0.475 (0.733)
	Completion time	0.719 (0.064)	0.760 (0.027)	0.543 (0.495)

repeated for the two remaining conditions. Finally, a brief discussion was conducted to gather participant's accounts of the various locomotion systems, such as qualitative preferences and opinions. The experiment lasted about 60 minutes per participant.

3.7 Data Analysis

The Shapiro-Wilk test indicated significant deviations from normality for several variables ($p < 0.05$). As a result, non-parametric Friedman tests [32] assessed statistically significant differences between locomotion techniques across the collected measurements. Post-hoc pairwise comparisons between the three VR locomotion techniques were conducted using Wilcoxon signed-rank tests with Bonferroni correction. The evaluation uses common language effect sizes (CLES), which in the Wilcoxon test are calculated from matched pairs rank-biserial correlations [25]. CLES provides a more straightforward interpretation as it denotes the percentage of time a participant from condition A is likely to have a higher or equal outcome measure than a person in condition B [51]. Therefore, a statistically significant CLES result >0.5 implies higher outcome values in game mode A, and <0.5 implies lower outcome values than in game mode B. All data was compiled and analyzed using Python v3.10 and the packages pandas, scipy, and pingouin [50].

4 Results

The results indicate *head tilt* or *arm swing* in 3PP elicit a higher sense of embodiment than a *controller joystick* when moving virtual avatars. Moreover, *arm swing* was perceived as more natural than *head tilt*. However, both *head tilt* or *arm swing* lead to higher task completion time and induce more VR sickness compared to using a *controller joystick*. The summary of the results is in Table 1, and the detailed results are described below.

4.1 Sense of Embodiment

Head tilt and arm swing led to higher sense of embodiment compared to controller joystick. The omnibus tests indicated statistically significant differences between locomotion techniques in total SoE ($\chi^2(2) = 25.4, p < 0.001$). Similarly, significant differences were found in the individual scales of body-ownership ($\chi^2(2) = 14.4, p < 0.001$), agency ($\chi^2(2) = 18.34, p < 0.001$), and self-location ($\chi^2(2) = 7.42, p = 0.024$).

Pairwise Wilcoxon signed-rank test indicated that both arm swinging ($CLES = 0.932, p < 0.001$) and head tilting ($CLES = 0.834, p < 0.001$) elicited greater total SoE than using a controller joystick. These findings were consistent across the three dimensions of SoE, as shown in Figure 3. The interpretation of the large effect size refers to the fact that 93.2% of the time, a participant using arm swinging for VR locomotion in 3PP would have higher SoE than a person using a controller joystick. Moreover, arm swing presented higher total SoE ($CLES = 0.684, p = 0.028$) when compared with head tilt. The perceived embodiment was mainly driven by the sense of agency ($CLES = 0.709, p = 0.016$), as shown in Figure 3, and the subscales of body ownership and self-location did not present significant differences.

4.2 Perceived Usability

Results indicated statistically significant differences in total usability score ($\chi^2(2) = 15.71, p < 0.001$), perceived easiness ($\chi^2(2) = 10.55, p = 0.005$), and naturalness ($\chi^2(2) = 16.62, p < 0.001$) according to the Friedman tests. The components of fun and exhaustion did not present significant differences across locomotion techniques.

The controller joystick presented better total usability than head tilting ($CLES = 0.826, p < 0.001$) according to the pairwise Wilcoxon signed-rank tests. Subscale comparisons support these findings, suggesting that locomotion through the controller was easier ($CLES = 0.852, p < 0.001$), more natural ($CLES = 0.783, p < 0.001$), and less fatiguing ($CLES = 0.297, p = 0.014$). Nevertheless, arm swinging also presented better total usability than head tilting ($CLES = 0.686, p = 0.026$) and did not present significant differences with controller joystick. Overall, head tilt was perceived as the least natural ($Md = 4, IQR = 2.3$) and most tiring ($Md = 4, IQR = 3$) among the three locomotion techniques, as shown in Figure 3.

4.3 VR Sickness

The average of two subscales of VR sickness, oculomotor and disorientation, produced the total VR sickness score. There were statistically significant differences between locomotion techniques regarding total VR sickness ($\chi^2(2) = 11.033, p = 0.004$) and the oculomotor subscale ($\chi^2(2) = 12.96, p = 0.001$). No significant results were found regarding disorientation ($\chi^2(2) = 3.51, p = 0.11$).

The results from the pairwise comparisons illustrate that controller joystick locomotion resulted in the slightest VR sickness compared to head tilt ($CLES = 0.223, p = 0.003$) and arm swinging ($CLES = 0.24, p = 0.014$). The effects on the oculomotor aspects of VR sickness, such as general discomfort, fatigue, eye strain, or difficulty focusing, mainly drive these findings. None of the pairwise comparisons presented significant differences regarding disorientation, which refers to headaches, dizziness, and vertigo.

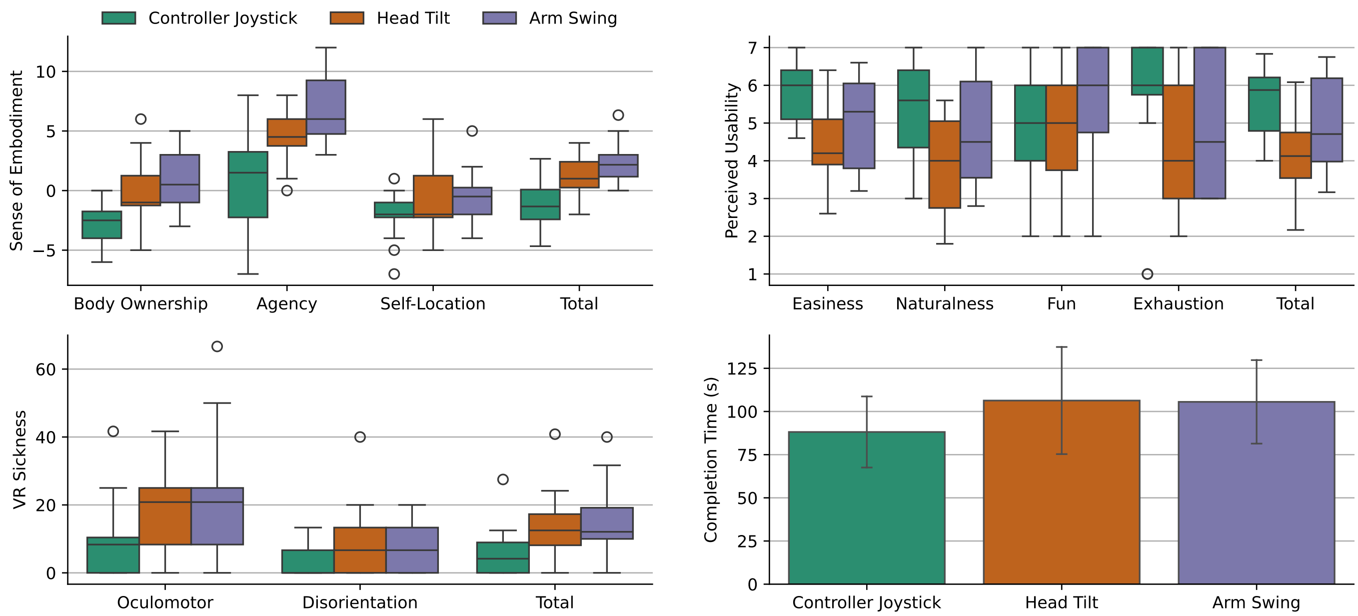


Figure 3: Results overview for each locomotion technique and dependent variable. Responses from 7-point Likert scales are grouped according to each questionnaire's guidelines. Completion time only includes trials completed within 10-min limit.

4.4 Completion time

Four trials did not complete the navigation task within the 10 min time limit and were therefore excluded from the analysis in Figure 3. The results showed that participants required less time traversing the environment in 3PP when using controller joystick ($M = 120s, SD = 129$) rather than head tilt locomotion ($M = 137s, SD = 127$) or arm swinging ($M = 167\ s, SD = 170$) with large effect sizes (0.719 and 0.760, respectively) that support the premise that controller joystick is the easiest to use. There were no significant differences in completion time between arm swing and head tilt locomotion techniques.

4.5 Post-experiment discussion

The post-experiment discussion mainly focused on the usability and gameplay of the different VR locomotion techniques rather than SoE. Participants found the controller joystick to be the easiest and most conventional. Arm swing was the most engaging and preferred since it let participants look around quickly and had similarities with Nintendo Wii interactions. The head tilt technique was the least favoured due to navigation difficulties, but participants suggested it for complementary interactions such as ducking or strafing sideways. Sentiments regarding VR sickness unveiled varying opinions. Some found the arm swing rotation mechanism uncomfortable, whereas others felt it helped alleviate motion sickness. The head tilt locomotion caused slight nausea but was not severe enough to end the experiment prematurely.

5 Discussion

This work aimed to understand how three VR locomotion techniques in 3PP influence the user's perception of embodiment towards an avatar. In general, we discovered that arm swinging is the best mechanism to maintain high levels of embodiment, although the locomotion time and induced sickness are slightly higher than traditional controllers. Moreover, head tilting was found as tiring and unnatural. The results' implications are discussed below.

5.1 Embodiment through Approximation of Body Movements

As evident from the descriptive data, the component of self-location remains consistently low across locomotion techniques. This outcome aligns with previous research [19, 47] that has identified viewpoint as the primary factor influencing this dimension of SoE. A low self-location score was anticipated since all game modes employed a 3PP perspective.

Moreover, the largest variation, coupled with significant differences between all pairwise comparisons, was observed in the agency scores. This outcome emphasizes the sensation of being the cause of one's actions. Given that the various locomotion techniques employ different input modes to move the virtual avatar, the diversity in how this dimension of SoE was perceived is to be anticipated. The results demonstrate that the bodily engagement of a locomotion technique correlates with higher agency scores. The arm swing technique, which is the most physically active, led to the highest agency levels. This finding echoes previous research on visuomotor synchrony and bodily obedience [9, 26].

Although the movement involved in the arm swing locomotion most closely resembles the avatar's movement compared to other methods, the player's arm swing and the avatar's arm swing were not synchronized. The virtual avatar in the current experiment employs a predefined running animation that is not directly synchronized with the user's movement, as would be the case in body-tracking scenarios [42]. This suggests that full visuomotor synchronization, achieved with body-tracking technologies, may not be strictly necessary to enhance the sense of agency. The sensation of agency appears to arise when users can anticipate their actions leading to predictable avatar movements, even if those movements are not fully synchronized. This observation could explain the fact that most participants anticipated the avatar moving faster when they swung their arms faster.

However, this result does not discount the possibility that achieving full visuomotor synchrony with the virtual avatar, such as through full-body tracking, might result in higher SA scores than the approach adopted in the experiment. Prior research on body-tracking in VR [42] has shown that skeletal body-tracking which drives avatar movement indeed heightens embodiment in virtual environments. Additionally, a few participants reported that even the slightest asynchrony between their physical body and the movements of the virtual avatar disrupted their SoE. Additional research into how varying levels of synchronization affect agency and user experience in 3PP VR could provide valuable insights into trade-offs between full-body tracking and predefined animations.

5.2 Joystick to Navigate and Body to Feel

Controller-based locomotion emerges as significantly easier to navigate than head tilting. This discrepancy might be attributed to the dual functionality of head rotation in head tilt locomotion, which requires users to constantly monitor and adjust their head orientation for both tasks, thus increasing mental effort. This challenge becomes apparent when tilting the head upward or downward to move forward or backwards, resulting in reduced visibility of the game view, which makes it difficult to perceive the current direction of movement. The apparent dual functionality of head rotation inherent to the head-tilt locomotion technique contribute to navigation challenges and increased cognitive load, which influence the reduced usability and overall user experience. Additionally, it can be inferred that using roll and pitch rotation of the headset as an input method is notably less precise than other input modes, which may lead to prolonged task completion time and increased user frustration. These factors explain why head tilting was perceived as less usable compared to controller-based locomotion, despite the enhanced embodiment through physical engagement.

Moreover, arm swinging is perceived as more fun, and the preference for this locomotion technique suggests that it offers an appropriate level of challenge compared to the other options. However, similarly to the head-tilt locomotion technique, the cognitive load and fatigue after prolonged use of the arm swing locomotion technique influence the task efficiency and usability. The arm swing locomotion requires the player to plan their route and rotation and adjust according to the change in perspective, while constantly swinging their arms to move forward. These factors would require more mental effort, as well as physical, than controller joystick locomotion, a conclusion supported by previous research on locomotion techniques and cognitive load in VR [14]. It should be noted, however, that while the arm swing locomotion technique exhibits the most considerable variance in completion time, this outcome might not solely reflect the challenge of the locomotion technique or increased cognitive load. In this game mode, the completion time was extended because several tools occasionally failed to disappear as the avatar collided with them, requiring players to move away from the tool and try again.

The lack of a significant difference in perceived naturalness between controller joystick and arm swing techniques could stem from varying interpretations of what naturalness entails. Participants may have considered the context of gaming mechanics or real-life movement, this ambiguity may clarify why head tilting as a form of input is perceived as relatively unnatural; since it does not align with real-life movements or typical gaming interactions.

5.3 Body Movements linked to VR Sickness

The descriptive data of the VRSQ indicate that arm swing and head tilt locomotion cause comparable levels of oculomotor symptoms and disorientation, with the most significant effect being observed in oculomotor symptoms. Due to the navigational challenges of head tilt locomotion discussed in the previous section, it is expected that the severeness of the experienced disorientation would be higher than, for instance, controller joystick locomotion, which did not exhibit the same challenges. Similarly, it is expected that arm swing locomotion causes higher levels of both disorientation and oculomotor symptoms due to the changing perspective when rotating and the fact that the game view would slightly 'judder' when the perspective changes, as the rendering of the virtual environment is out of sync with the headset rotation.

There are differing opinions on which game mode caused the least VR sickness and why. According to previous research on sensory conflict theory, VR sickness arises from a mismatch of visual and vestibular cues [40], such as a moving viewpoint with a stationary physical body. However, the statistical analysis of the VRSQ in this study suggests that this explanation may not hold for most individuals within the context of the conducted experiment. Particularly, most participants found the controller joystick locomotion, where the physical body is completely stationary while the view port is moving, to cause the least motion sickness. This outcome could stem from the constrained field-of-view resulting from the 'orb' effect, implemented to mitigate the impact of a moving environment. When paired with joystick based input, the game mode's resemblance to traditional console gaming is enhanced, thus inducing minimal VR sickness.

The participants' familiarity with VR, with most using it frequently, may have influenced the outcomes of the VRSQ scores. Individuals accustomed to navigating virtual environments may exhibit greater tolerance for sensory discrepancies, potentially mitigating the extent of VR sickness compared to those with limited prior VR exposure.

5.4 Limitations

Three main limitations are evident in the present study. Firstly, the average completion time for the game was relatively short. This might have limited participants' exposure to the virtual environment, potentially affecting their sense of embodiment and thereby influencing the validity of the results. Longer duration of exposure could have led to more pronounced differences in the dependent variables across conditions.

Secondly, the participants' previous experience with VR, with most possibly being considered experts, could have influenced their perceptions of the usability of the locomotion techniques. Their familiarity with VR interaction paradigms and functionalities might have affected their judgments. As previously mentioned, the participants' experience with VR could have influenced the results of the VRSQ, as those accustomed to VR might be more tolerant of VR sickness and perceive its effects differently compared to individuals with no prior VR experience. A more diverse sample of participants, including individuals with varying levels of familiarity with VR, could have potentially yielded more variance in the results, thus increasing the generalizability of the conclusions.

Thirdly, along with changing modes of locomotion, the camera behaviour of the conditions varies. While the camera works as a traditional VR camera in the controller joystick condition, allowing the user to look around in the virtual environment outside of the game view 'orb', the camera also controls the movement of the avatar and the rotation of the player in the head-tilt locomotion and arm swing locomotion, respectively. This configuration could have considerable effects on the perceived usability and VR sickness measures of each condition which were not accounted for in the study.

5.5 Future Work

Due to the emerging discourse in 3PP VR, a promising avenue for future research involves the exploration of the effects of different interactions on the acceptance of 3PP VR. Many participants remarked on the novelty of experiencing a VR game in 3PP and expressed keen interest in the concept, thereby underscoring the need for additional research in this domain. For instance, a key area worth expanding on is how different constraints of the field-of-view might influence comfort and immersion in virtual environments in 3PP. Investigating the effects of the limited field-of-view was deemed to be outside the scope for this study, and was solely used to ensure the physical well being of the participants during the experiment. However, this direction for future research could bring insights into the trade-offs between immersion and comfort and aid in finding an optimal balance.

Furthermore, novel locomotion techniques in 3PP could emerge using the advanced functionalities inherent in consumer VR headsets, such as full-body tracking to ensure complete visuomotor synchrony between the user and the virtual avatar. Lastly, exploring the relationships between locomotion, avatar representation, and accessibility for users with physical impairments would be a valuable extension of the current research. This focus would also highlight the needs of an underrepresented group of VR users and contribute to the accessibility of the technology.

6 Conclusion

This study aimed to contribute to the evolving discourse on 3PP VR by examining the impact of different locomotion techniques on SoE and user experience, specifically focusing on perceived usability and VR Sickness.

Our findings suggest that locomotion techniques generally exert the most significant influence on SA in 3PP VR. At the same time, SSL remains consistently low regardless of the locomotion technique employed, a trend that aligns with previous research. Moreover, locomotion techniques that incorporate visuomotor synchrony, even indirectly where users mimic the movements of the animation, such as the arm swing locomotion technique, are correlated with higher levels of SoE in 3PP VR. The arm swing locomotion technique elicited the highest SoE and was the most engaging and preferred by participants.

Interestingly, despite the preference for a locomotion technique requiring more movement from the player, the statistical analysis points towards a stationary physical body with a moving viewport, i.e. the controller joystick locomotion technique, which is reminiscent of the interactions on a console or PC, induces the least motion sickness. This finding contradicts established research on sensory discrepancies and motion sickness. However, it is worth noting that some participants expressed sentiments that challenge this result, suggesting that visuomotor synchrony may alleviate VR sickness. These results suggest that while more active techniques improve embodiment, they may also increase discomfort, highlighting a trade-off in VR design.

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