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The Cognitive Load and Usability of Three Walking Metaphors for Consumer Virtual Reality

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ABSTRACT

Walking metaphors have been extensively researched for travel in virtual reality (VR) applications. However, only a few walking metaphors are feasible for most consumer VR systems. In this paper, we present a study that compares three of these suitable metaphors: Scaled Walking, Human Joystick, and Walking-In-Place. Our study empirically assesses the cognitive loads and travel performances of these three walking metaphors by employing a novel dual-task methodology. We also evaluated their effects on simulator sickness, presence, and perceived usability. The results of our study indicate that Scaled Walking afforded significantly better travel performances and perceived usability than Human Joystick and Walking-In-Place. Our results also indicate that Walking-In-Place required the worst cognitive loads and that Human Joystick induced the worst simulator sickness. Given these results, we discuss the implications of using a high-fidelity, full-gait walking metaphor.

Keywords: Cognitive load, 3D travel techniques, virtual reality.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 INTRODUCTION

Virtual reality (VR) is a complex field that uses cutting edge technologies to create high-fidelity sensory stimuli and natural interactions [7]. In recent years, millions of consumers have experienced VR due to new technologies, such as the HTC Vive and the Oculus Rift [44]. These technologies enable realistic experiences and interactions, such as maneuvering via head tracking [42] and using virtual hands to manipulate objects [3]. However, *travel*—the physical task of moving to a new target location or in a new direction—is one aspect of interacting with consumer VR systems that is still limited [25].

Many consumer VR applications use teleportation for travel, in which the user selects a destination and their location within the virtual environment is automatically updated to match the destination [14]. The major benefit to using teleportation is that it induces little, if any, simulator sickness, but at the cost of reducing spatial awareness [23]. On the other hand, several VR applications also offer some form of steering, in which the user continuously controls the direction of travel [25]. Steering has been shown to afford greater spatial awareness than teleportation [5], but with increased risk of simulator sickness [15].

Aside from teleportation and steering, VR researchers have investigated numerous walking metaphors [25]. However, few of these have been incorporated into consumer VR experiences [15]. Some metaphors, such as real walking and redirected walking, often rely on large tracking areas [51], as opposed to the room-scale dimensions of most consumer VR setups. Other metaphors require additional hardware and devices in order to negate the user's physical movements [25], such as the Virtuix Omni.

Some walking metaphors are generally more feasible for consumer VR experiences. For example, the Scaled Walking metaphor enables the user to travel through a virtual environment larger than the physical space by scaling their horizontal movements [19]. The Human Joystick metaphor employs the 2D horizontal vector from the center of the tracking space to the user's tracked head position as the travel vector [30]. Another feasible walking metaphor is Walking-In-Place, which allows the user to make a gesture, usually marching, to indicate travel.

In this paper, we present one of the first studies to empirically compare Scaled Walking, Human Joystick, and Walking-In-Place. The goal of our research was to evaluate the usability and travel performances of these three walking metaphors. In addition to travel performance, we also aimed to assess the cognitive load of using these three techniques, as cognitive load has been shown to interfere with travel tasks [27]. For this purpose, we have designed and implemented a novel dual-task methodology that employs a horizontal, multi-directional travel task and a standard n-back cognitive task [62].

Using this novel methodology, we have conducted a counterbalanced, within-subject user study with 30 participants. In addition to the cognitive and travel task performances, we also assessed simulator sickness, presence, and perceived usability for each travel technique condition. The results of our study indicate that Scaled Walking afforded the best travel performances and perceived usability. Our results also indicate that Walking-In-Place required significantly more cognitive load than Scaled Walking and Human Joystick. Additionally, we found that Human Joystick induced significantly more simulator sickness than either of the other two walking metaphors. We discuss the potential reasons for these results and their implications in the paper.

2 RELATED WORK

There are many different 3D travel techniques proposed and used in previous VR studies and systems. Among all these techniques, only a few have been investigated in terms of cognitive load. In this section, a taxonomy of 3D travel techniques is briefly introduced, followed by a discussion of walking metaphors. We then discuss prior evaluations of travel cognitive demands.

2.1 A Taxonomy of 3D Travel Techniques

As discussed, travel is the motor component of navigation (i.e., the physical actions required to move from one location to a new destination) [25]. Travel is especially important, and difficult, in VR because virtual environments are often much larger than the physical space being tracked. Hence, researchers have proposed and investigated many different 3D travel techniques. LaViola et al. [25] have organized many of these techniques into a taxonomy

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consisting of four common approaches: 1) Walking metaphors, such as Scaled Walking [19] and Human Joystick [30]; 2) Steering metaphors, such as gaze-directed steering [34] and lean-directed steering [21]; 3) Selection-based travel metaphors, such as dual-target techniques [64] and route-planning techniques [18]; and 4) Manipulation-based travel metaphors, such as camera manipulation [61] and avatar manipulation [52]. Of these four different approaches, our research focuses on walking metaphors, which have not been thoroughly investigated for consumer VR technologies. In the next section, we discuss prior walking metaphors in greater detail.

2.2 Walking Metaphors

LaViola et al. [25] further classify walking metaphors into three categories based on human gait: full-gait, partial-gait, and gait-negation techniques. We briefly review those approaches and relevant techniques here.

Full-gait techniques are walking metaphors that afford all the events and biomechanics involved in the human gait [25]. Among these techniques, real walking is the most direct and obvious full-gait technique. Real walking has been shown to increase presence (i.e., the sense of "being there") [60] and spatial knowledge [10]. However, it is often not feasible to only use real walking to travel, as many virtual environments are larger than the physical tracking space. Hence, we did not investigate it in our study.

Redirected walking is another full-gait approach, in which the travel technique attempts to redirect the user away from the boundaries of the physical tracking space while walking [17, 43, 46]. There are two common approaches to redirection: overt and subtle [54]. Overt redirected walking techniques make obvious changes to the mapping between the physical and virtual spaces, such as rotating the virtual world around a stationary user [46]. On the other hand, subtle redirected walking techniques attempt to imperceptibly change the mapping, such as continuously rotating the virtual environment to steer the user towards the center of the tracking space [17]. However, Steinicke et al. [51] have found that a very large tracking space (44 m in diameter) is necessary for redirected walking to be completely imperceptible. Since room-scale VR systems use a much smaller tracking space, we did not investigate redirected walking in our study.

Another full-gait travel approach is Scaled Walking. It is implemented by scaling the user's movements, such that one physical step covers a much larger distance in the virtual space. Interrante et al. [19] investigated one implementation of Scaled Walking, called Seven League Boots, in which only the user's intended direction of travel is scaled. While this intended direction can be estimated as a weighted combination of the user's gaze direction and recent horizontal displacement, it can induce simulator sickness due to scaling lateral motions when incorrect. Alternatively, Interrante et al. [19] proposed simply allowing the user to press a button to apply a uniform horizontal scale factor, which is what we investigated in the current study.

Unlike the full-gait techniques, partial-gait techniques focus on recreating specific aspects of the gait cycle to provide seminatural interactions for travel. Human Joystick is one such technique. The concept is that the user's body acts like the handle of a joystick to initiate travel in different directions [30]. This is most often accomplished by using the 2D horizontal vector created from the center of the tracking space to the user's tracked head position to determine the direction and velocity of virtual movement [25]. Human Joystick has been shown to afford greater presence than steering [30], but worse travel performances [28, 29]. It has also been shown to require more cognitive load than real walking [28]; however, it has not been previously compared to other walking metaphors in terms of cognitive load, which we do in our study.

Walking-In-Place is another partial-gait technique, in which the user steps their feet as if walking, but while remaining in the same physical space [25]. Nilsson et al. [38] identified three gestures for Walking-In-Place: marching (lifting the feet upward), wiping (pulling the feet backward), and tapping (lifting the heel, but not toes, upward). However, many implementations only support marching [13, 49, 60, 65]. Walking-In-Place requires physical exertion similar to real walking [31] and has been shown to afford greater presence than steering [60]. We investigated Walking-In-Place to compare its required cognitive load and travel performances to the other walking metaphors.

Gait-negation techniques, the third category of walking metaphors, use devices to keep the user in the same physical space while performing semi-realistic walking motions [25]. Prior researchers have investigated numerous devices for gait negation, including treadmills [39], omnidirectional treadmills [11], stepping devices [20], low-friction surfaces [57], and giant "hamster" balls [33]. While these devices simulate real walking and avoid physical space limitations, they often induce imbalance due to mismatches between the user's physical inertia and the device's inertia [25]. The additional hardware requirements also make them less feasible for broad consumer adoption. Hence, we did not investigate any gait-negation techniques in our study.

2.3 Cognitive Demands of 3D Travel Techniques

Several prior studies have investigated the cognitive loads of various travel techniques using either a post-task or dual-task paradigm. A post-task paradigm involves performing some type of travel task and then performing a cognitive short-term memory task regarding some informational aspects of the travel experience [6, 28, 53, 56, 63]. On the other hand, a dual-task paradigm involves performing a cognitive working-memory task while concurrently performing a travel task [4, 9, 55].

2.3.1 Post-Task Paradigms

Bowman et al. [6] conducted one of the earliest evaluations of the cognitive load of travel. They evaluated and compared gaze-, hand-, and torso-directed steering using a post-task paradigm, in which participants traversed corridors with word signs and then recalled the position, surface, and word of the signs after travel. Bowman et al. [6] did not find any significant cognitive differences in their study.

Zanbaka et al. [63] conducted a very different post-task study investigating real walking, gaze-directed steering with six degrees of freedom (6-DOF), gaze-directed steering with 3-DOF, and a non-spatial joystick steering technique. Their travel task was to explore a large virtual room populated with furniture and many realistic objects for five minutes. Their post cognitive tasks were a cognition questionnaire, with questions like "How wide was the couch?" and sketching top-down maps of the room. In general, they found that real walking required fewer cognitive demands than the steering techniques.

Suma et al. [56] conducted a similar post-task study of real-world walking (in the physical world), real walking (in the virtual world), and gaze-directed steering. Their travel task involved exploring a simple maze with branching paths and 12 objects distributed throughout for five minutes. Like Zanbaka et al. [63], Suma et al. [56] used a similar cognition questionnaire. They also used object recall and placing the objects on a map as additional post cognitive tasks. In similar studies, Suma et al. [53, 56] employed traversing a linear maze for their travel task. In their studies [53, 55, 56], Suma et al. also found that walking generally required fewer cognitive demands than steering.

Marsh et al. [28] took a different post-task approach for comparing real walking, Human Joystick, and non-spatial steering. In their approach, each trial began with the presentation of either a spatial or verbal sequence. Participants then used the assigned travel technique to move to a target five feet away. Participants were then asked to recall the presented sequence. Like Zanbaka et al. [63] and Suma et al. [53, 55, 56], Marsh et al. [28] found that real walking require fewer cognitive demands than their virtual travel techniques.

2.3.2 Dual-Task Paradigms

Dual-task paradigms involve performing a cognitive working-memory task while concurrently performing a travel task [9, 55].

Suma et al. [55] conducted a dual-task study investigating real walking, gaze-, hand-, and torso-directed steering. Their travel task involved following a moving red sphere through a grid-based virtual environment as closely as possible. Their concurrent cognitive task involved listening to a word every five seconds and pressing a button if the word belonged to a previously assigned conceptual category (e.g., “parts of the body”). Their results indicated that real walking required less cognitive load than the virtual steering techniques, similar to the previous post-task studies. One problem with the dual-task approach used by Suma et al. [55] is that familiarity, or unfamiliarity, with the words and categories can disproportionately affect the results.

Most similar to our dual-task paradigm, Bruder et al. [9] used a standard two-back working memory task [41] while following a virtual path. Their two-back cognitive task involved pressing a button if the currently presented stimulus matched the stimulus presented two trials before in a series of stimuli. They used a verbal version consisting of letters only and a spatial version with a symbol oriented at one of four angles. Their results indicate that increasing curvature gains during redirected walking increases cognitive load. Unlike the approach of Suma et al. [55], the approach of Bruder et al. [9] is not prone to prior familiarities or knowledge. Hence, for our study, we decided to adopt the same type of cognitive task for our dual task.

3 Dual-Task Walking Metaphor Study

The purpose of this study was to systematically evaluate the cognitive load and travel performance of Human Joystick, Scaled Walking, and Walking-In-Place using a dual-task paradigm, similar to previous researchers [9, 56], and to compare the three travel techniques in terms of simulator sickness, presence, and perceived usability. We conducted the study using an HTC Vive, a consumer VR system.

3.1 Cognitive Task

For our study, we used a standard n-back working memory task, in which the participant is expected to observe a series of stimuli and to indicate when the currently presented stimulus is the same as the one presented n trials before [41]. We conducted pilot studies to determine the type of stimulus (i.e., verbal or spatial) and value of n to use (see Figure 1). We found that spatial stimuli and more than 2-back tasks were overly difficult for participants to use our spatial steering techniques. Hence, for our actual study, we used the same verbal two-back cognitive task that Bruder et al. [9] used, which requires the participant to press a button if the presented letter is the same as the one presented two letters back in the sequence. This task differs slightly from traditional n-back tasks, which normally require the participant to press one button to respond to a stimulus as a target and a different button to respond to a stimulus as a nontarget [40]. However, like Bruder et al. [9], we chose to only require a button press (the Vive trigger button) for target stimuli to keep the cognitive task from potentially interfering with the travel techniques by monopolizing the most ergonomic button inputs and from potentially suffering due to using an unergonomic button. Each letter stimulus was randomly selected from the set {A, B, C, D} and displayed for 500ms with a pseudo-randomized inter-stimulus interval of 1100-1500ms, like Bruder et al. [9].

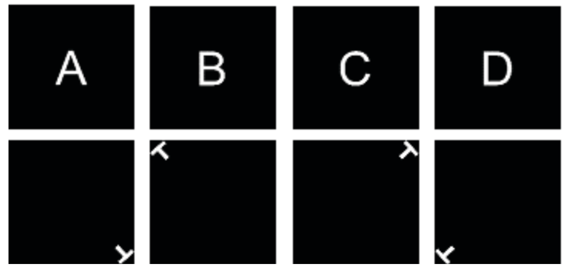

Figure 1: The verbal and spatial cue examples used in our pilot studies. The top row shows four letter cue examples used in the study, and the bottom row shows four T-shape cue examples.

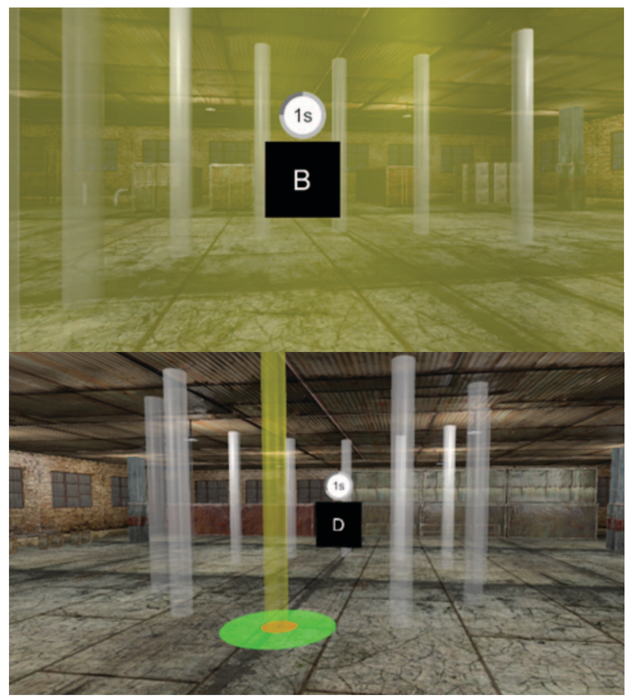

Figure 2: The letter cue and timer used in the experiment. Top image shows a third-person view, and bottom image shows a first-person view.

3.2 Travel Task

We modeled our travel task after the standardized selection task of ISO 9241-9, which requires the user to make a series of selections from a ring of objects, in which the target alternates sides of the ring while continuing clockwise [50]. This selection task was proposed as a standard task for Fitts’ Law research [50]. It has since been used to investigate the effects of input device latency and spatial jitter [58], stereo and mono-rendered cursors [59], ray-casting techniques [35], intersection disambiguation techniques [36], and tilt-based interactions [26]. See Figure 3 for a depiction of the conventional multidirectional selection task.

For our travel study, we modified the multi-directional selection task to be a multi-directional travel task by rotating the normally vertical task to the horizontal plane. We used semi-transparent vertical columns to represent the objects comprising the ring (see Figure 4). Instead of selecting the current target (highlighted blue), participants were required to stop and remain within the target column for two seconds, conveyed by a countdown timer and a yellow highlight (see Figure 2), before proceeding to the next target. In addition to requiring travel termination, this time-based interaction also avoided requiring an additional button input, which would introduce additional cognitive load for recalling which button to press for selection.

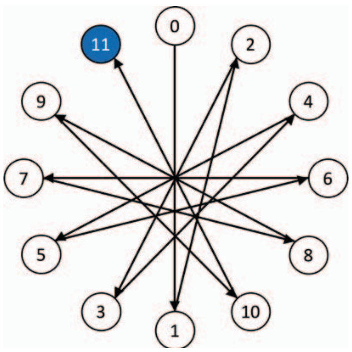

Figure 3: The Fitts' Law task used for many pointing and selection studies. Each circle represents a selection target and the targets are to be traversed in the order of the arrows and numbers.

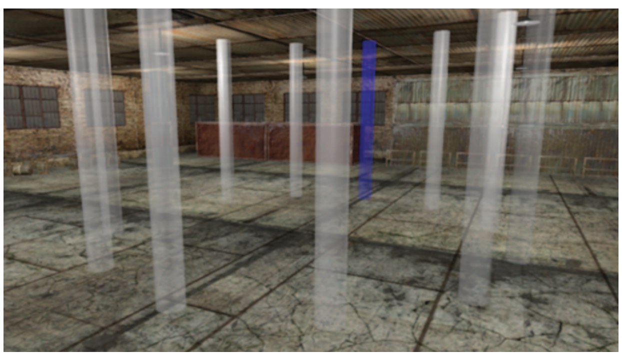

Figure 4: The Fitts' Law task adapted as the travel task used for our experiment. Each column represents a waypoint for the user to traverse to. The yellow and green circles are used for Human Joystick to represent the no travel zone and tracking area.

Our multi-directional travel task also has two adjustable parameters—movement distance (D) and target width (W)— like the original multidirectional selection task [50]. For this study, we set movement distance to 10 meters and target width to 0.5 meters for all tasks. For movement distance, we wanted a distance larger than what most VR consumers will have accessible to them for walking (i.e., an average room is approximately 3m x 3m) but also short enough to be a common continuation distance for most VR applications. For target width, we used 0.5 meters because it should fit an average human shoulder width [12]. We chose to use a ring of 12 targets, as Moore et al. did [35, 36], to ensure a sufficient number of tasks while also avoiding excessive trials.

3.3 Travel Techniques

We investigated three walking metaphors in this study: Scaled Walking, Human Joystick, and Walking-In-Place.

For Scaled Walking, we chose to implement the technique proposed by Interrante et al. [19], in which a horizontal constant scale factor (C_{SW}) is applied to the user's movements while pressing a button. For our implementation, the participant had to press and hold the Vive touchpad button to activate Scaled Walking. Equation (1) shows how the horizontal position of the tracking space's origin within the virtual environment (Txz) was updated by scaling the change in the horizontal position of the user's head (Hxz) and adding it to the tracking space's origin. See Figure 5 for a depiction of our Scaled Walking implementation.

If the participant walks without pressing the button for Scaled Walking, then the participant's virtual head position is translated one-to-one with the physically tracked position (i.e., without any scale applied). During the experiments, we did notice that some participants would deactivate Scaled Walking once near the target, in order to simply take a small step or two to fit within the target. Technically, it was possible for a target to become unreachable if a participant chose to walk across the tracking area without activating Scaled Walking, but none of our participants made this mistake during our study.

$$Txz_{n+1} = \left(C_{SW} \times (Hxz_{n+1} - Hxz_n)\right) + Txz_n \tag{1}$$

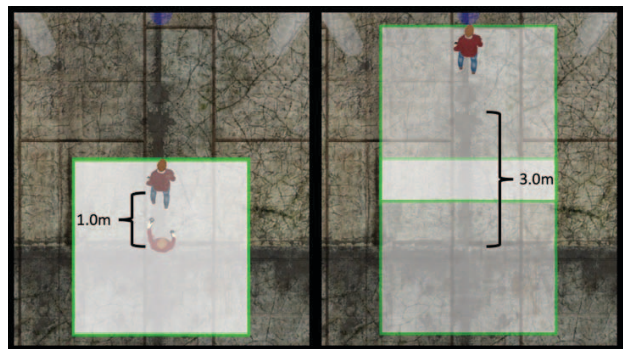

Figure 5: Depiction of our Scaled Walking condition. By physically walking 1.0m within the tracking space (left), the tracking space's origin is translated 3.0m within the virtual environment (right).

For Human Joystick, we chose to implement the technique presented by McMahan et al. [30], as opposed to some of the other variants (e.g., [28]). The technique calculates a 2D travel vector by subtracting the tracking space's origin from the user's horizontal head position. It then multiplies this travel vector by a constant scale factor (C_{HJ}), before adding it to the tracking space's origin (see Equation (2)). The technique also uses a no-travel zone (shown in red in Figure 6) to avoid constant travel due to small differences in the precision of the tracking. For our study, we used a no-travel zone with a diameter of 1.0 meter to afford the ability to walk and turn around without activating travel.

$$Txz_{n+1} = \left(C_{HJ} \times (Hxz_{n+1} - Txz_{n+1})\right) + Txz_n \tag{2}$$

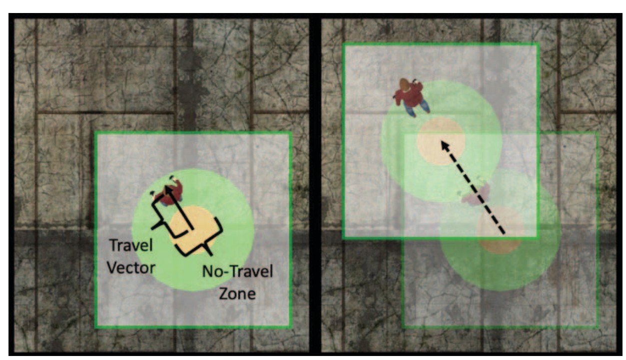

Figure 6: Depiction of our Human Joystick condition. By physically walking out of the red no-travel zone (left), the tracking space's origin is translated along the travel vector (right).

For Walking-In-Place, we implemented a variant of the algorithm presented by Nilsson et al. [38]. We attached Vive trackers to the participant's ankles for tracking their 6-DOF movement and used their orientations ($LFOxz$ and $RFOxz$, for left and right foot orientations, respectively) to calculate the unit travel vector like Nilsson et al. [38]. Prior to the condition, we calibrated an expected step height for the participant (the green line in Figure 7), also like Nilsson et al. [38]. This afforded participants to use either a marching or a tapping gesture to active Walking-In-Place. We originally implemented a dynamic scale factor based on the expected step height as Nilsson et al. [38] did, but during pilot testing of our study, we found that participants were overshooting the targets. This was due to participants attempting to physically step into the targets, once near them, but the step also created a positive scale factor, which resulted in a double movement (one physical and one virtual). It is important to note that the travel task used by Nilsson et al. [38] purposefully did not include terminating travel, unlike our study.

To address this type I error (false positive) issue, we adopted an expected stance height as a lower threshold (the red line in Figure 7) for distinguishing between the Walking-In-Place gesture and real walking. Once a step reaches this expected stance height, after surpassing the expected step height, our algorithm calculates the horizontal distance between the current stance and the last stance. If that distance is greater than 0.3 meters, our algorithm disregards the step as real walking. Otherwise, our algorithm applies a constant step length (C_{WIP}) to the tracking space's origin. Figure 7 depicts how our algorithm distinguishes between Walking-In-Place and real walking. Equation (3) shows how the horizontal position of the tracking space's origin is updated when a Walking-In-Place gesture is detected.

$$Txz_{n+1} = \left(C_{WIP} \times \left(\widehat{LFOxz_{n+1} + RFOxz_{n+1}}\right)\right) + Txz_n \tag{3}$$

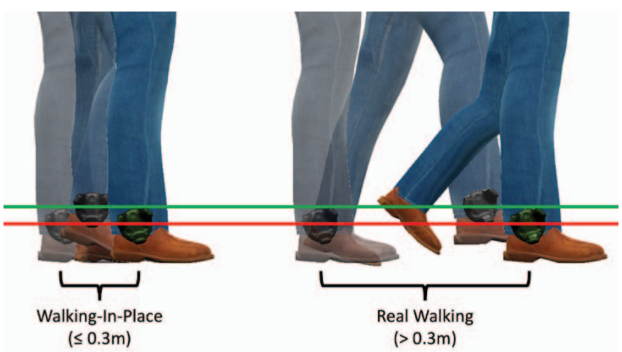

Figure 7: Depiction of our Walking-In-Place condition. The green and red lines represent the expected step and stance heights, respectively. Once a stance position is detected after a step, the distance between the current stance and the last is calculated. If this distance is less than or equal to 0.3 meters, Walking-In-Place is activated. Otherwise, the step is disregarded as real walking.

3.4 Travel Speed

The parameters of three travel techniques were carefully tuned so that they require approximately the same time to complete the travel task. It is quite important to make all the techniques have a theoretical chance to be the fastest, so that the time metrics will be of some value when comparing the three techniques.

According to previous studies [1, 2, 48], the average human walking speed is 1.44 m/s. Hence, the average time to cover the movement distance of the travel task in the real world would be 6.944 seconds (10 m / 1.44 m/s). While the constant scale factors of Human Joystick and Walking-In-Place could be adjusted to match this time, Scaled Walking could not, due to the limitations of the physical tracking space. Because our tracking space was only 4 meters by 4 meters, we had to use a scale factor of $C_{SW} = 3$ to allow the participant to virtually move up to 12 meters, which covered our travel task distance of 10 meters. However, by setting C_{SW} to 3, the average time to cover the task distance became 2.315 seconds (6.944 s / 3), which results in a task speed of 4.32 m/s (10 m / 2.315 s). Hence, we had to find appropriate scale factors for Human Joystick and Walking-In-Place for this speed.

For Human Joystick, the overall speed is dependent upon how far outside of the no-travel zone that the participants steps. We assumed that most participants would take a single step from the center of the no-travel zone to activate the technique. According to prior research [48], the average human step length is about 0.738 meters. For that estimated distance, we chose to set the Human Joystick scale factor C_{HJ} to 5.854 (4.32 / 0.738) for the target travel speed of 4.32 m/s.

Based on average walking speeds and step lengths, people normally take an average of 1.951 steps per second (1.44 / 0.738). To match the average task time of Scaled Walking, we calculated that participants would need to take 4.517 steps (2.315 s * 1.951 steps/s) to complete the task. To cover the task distance, that required setting the Walking-In-Place scale factor C_{WIP} to 2.214 meters per step (10 m / 4.517 steps).

It is important to note that the travel speeds used in our study (i.e., 4.32 m/s) were approximately three times higher than human walking speeds in the real world. However, many 3D travel techniques have employed higher speeds, such as 5 m/s [14] and even 50 m/s [45].

Figure 8: The apparatus used for our study. The tethered HMD was hung from a truss to avoid interfering participant movements.

3.5 Apparatus

We performed the experiment with an HTC Vive, including a head-mounted display (HMD), two controllers, two trackers, and two base stations. The two base stations were mounted to two tripods and faced each other to create a 4m × 4m tracking space. The subjects wore the Vive HMD, which provided a resolution of 1080 × 1200 pixels per eye with a refresh rate of 90Hz and an approximate 110° diagonal field of view. The HMD was tethered with an HDMI cable, a USB cable, and a power cable. To avoid interfering with the physical movements of participants, the cables were hung from a truss structure in the room. The two controllers are 6-DOF wireless devices with a trackpad and multiple buttons for input. The two Vive trackers were connected to the computer by Bluetooth. Two speakers were also used for audio feedback to indicate when the trigger button was pressed.

The application was developed and rendered with the Unity3D engine and ran on a Windows 10 computer. The task was orally instructed, and all questionnaires were presented via Qualtrics.

3.6 Metrics

Both subjective and objective metrics were used for the study. As for objective metrics, the experiment application recorded the times and user responses while the participant was doing the task.

With cues and recorded user responses, we were able to come up with a series of metrics to estimate the cognitive load. The first metric is accuracy, which has been looked at in most prior n-back test studies. The calculation is quite intuitive, which compares the participant responses with the corresponding expected responses and sums up all the correct ones and the total number of correct responses is divided by the total number of responses. The range of this correctness is [0, 1] with "1" representing that the participant gets all the responses right and "0" representing that the participant gets all the responses wrong.

Accuracy is simple to calculate, and the value can easily reflect the participant's performance. However, there is an issue with this calculation method. Since all the stimuli are randomly generated, the participant can automatically get roughly 75% of the responses correct by simply not pressing the trigger at any time. In order to counter that, a set of metrics commonly used in the information retrieval studies is used. These metrics include precision, recall and F-measure, and their calculations are shown below in the formulas. For each n-back task trial, there are four potential outcomes (see Table 1). Given these outcomes, *Accuracy* is defined by Equation (4), which does not distinguish between the number of correct matches and non-matches. On the other hand, *Precision* only considers the correctness of instances in which the participant responded with a button press (see Equation (5)). Similarly, *Recall* only considers the correctness of instances in which the trial was a match trial (see Equation (6)). Finally, the *F-measure* (see Equation (7)), sometimes referred to as the F1-measure, is the harmonic mean of precision and recall, and is widely used to evaluate the success of a binary classifier when one class (e.g., match stimuli) appears less frequently than the other (e.g., non-match stimuli).

Table 1: Potential outcomes of each cognitive task trial

	Match Stimulus	**Nonmatch Stimulus**
Button Press	TP (true positive)	FP (false positive)
No Press	FN (false negative)	TN (true negative)

$$Accuracy = \frac{TP + TN}{TP + FP + FN + TN} \tag{4}$$

$$Precision = \frac{TP}{TP + FP} \tag{5}$$

$$Recall = \frac{TP}{TP + FN} \tag{6}$$

$$F\text{-}Measure = 2 \times \frac{Precision \times Recall}{Precision + Recall} \tag{7}$$

For travel performance metrics, *Ballistic Time* is the time used in traveling from one target to the next. *Refinement Time* is measured from when the participant enters the target to the time when the participant stays still. The 2-second wait time is not considered in the Refinement Time. *Exit Time* is calculated from when the 2-second still time ends to when the participant exits the current target. *Trial Time* is the summation of Exit Time, Ballistic Time, and Refinement Time from one target to the next. *Total Time* is measured from the first exit stage to the last refinement, and all the 2-second wait times are removed from the Total Time. *Response Time* is the time between when the cue appears and when the participant presses the trigger to respond. For responses, whenever the participant presses the trigger, the system will record it as a response. The participants can press the trigger multiple times when a cue appears, but only one will be recorded.

As for subjective metrics, the Simulator Sickness Questionnaire (SSQ) [22] was used to measure simulator sickness. The iGroup Presence Questionnaire (IPQ) [47] was used to measure the sense of presence. The System Usability Scale (SUS) [8] was used to measure the perceived system usability. The participant's subjective preferences for the travel techniques were recorded for controlling events, the naturalness of the interactions, consistency with real world experiences, and anticipating of actions.

3.7 Research Questions and Hypotheses

With the detailed design of the comparison of 3D travel techniques, we were able to investigate several research questions with the experiment. For these research questions, hypotheses are also given based on our expectations of the study results.

R1. Which walking metaphor requires the least cognitive load?

H1. Scaled Walking will require the least cognitive load. Human Joystick requires the participants to pay attention to the travel speed by moving their bodies and Walking-In-Place requires the participants to lift their feet to a certain height to initiate travel. Compared to these two techniques, Scaled Walking only introduces one button press. Otherwise, the body movements are the same as real walking.

R2. Which walking metaphor affords the fastest travel?

H2. Human Joystick will afford the fastest travel. Since Scaled Walking may be affected by the size of the tracking space and the participants may spend time in adjusting their physical position to get to the target, we believe Scaled Walking will not be the best one in terms of time. Walking-In-Place requires the participants to adjust their physical positions when getting close to the targets, so it should also cost more time.

R3. Which walking metaphor induces the least simulator sickness?

H3. Scaled Walking will induce the least simulator sickness. Simulator sickness is believed to occur because of the conflict between the visual feedback and the vestibular feedback [16]. So, we predicted that Human Joystick was going to induce the most simulator sickness. Since our Walking-In-Place technique moves the participant's viewpoint slightly later than the participant's foot movement, we hypothesized that it would also induce some simulator sickness.

R4. Which walking metaphor provides the best sense of presence?

H4. Scaled Walking and Walking-In-Place will provide a better sense of presence than Human Joystick. Because our virtual environment was the same for all three walking metaphors, there should not be any change in presence due to the environment. However, due to the greater interaction fidelity of Scaled Walking and Walking-In-Place [32], we hypothesized that they would afford more presence than Human Joystick.

R5. Which walking metaphor is perceived as most usable?

H5. Scaled Walking will afford the most perceived usability. Scaled Walking only requires a button press to active it while the other two techniques involve several motor actions and body movements. The only problem with Scaled Walking is the limited tracking space. However, in our study, the scale factor was carefully selected to ensure that the participants could cover the virtual space within the real tracking space.

3.8 Procedure

The study took each participant approximately 60 minutes to complete. Each participant was presented with three different types of walking metaphors and two concurrent tasks. The order of the techniques was counterbalanced with a full-factorial permutation, so there were six different orders in total, and the participants were grouped into six cohorts accordingly.

At the start of the study, the participant was given two printed copies of the informed consent form, one to sign and return to the experimenter and one to keep for personal records. Then the participant was presented with a background survey to collect information about their background and experiences with computer games and VR. After the survey, the experimenter would give the participant information about the steps and tasks, and the participant was given the opportunity to ask questions.

A test was given after the participant was orally instructed. The participant needed to use real walking to complete the dual task like the real studies. The participant was required to get 75% accuracy in the test in order to proceed to the next step. Otherwise, the participant was required to reattempt the test.

The participant was presented with three different travel techniques which were Scaled Walking, Human Joystick and Walking-In-Place. For each travel technique, the participant was first trained how to use the technique to complete the travel task. After they were familiar with the travel technique, they were then asked to carry out the dual task. Immediately after finishing their task with one travel technique, they were asked to complete the series of questionnaires (SSQ, IPQ, and SUS) to assess their simulator sickness, presence, and perceived usability. Once the participant finished all three walking metaphor conditions, an exit survey would be presented for ratings and comments.

3.9 Participants

We recruited 30 unpaid participants for the experiment, among which 20 were male and 10 were female. The age ranged from 18 to 30 with a mean age of 22.4. Based on self-reported background data, three participants had no prior video game experiences. Half of the participants had experiences of immersive VR systems.

The participants were grouped into six cohorts with different travel technique orders to counterbalance potential ordering and learning effects. Analysis has been conducted on the data collected, and there was no significant ordering effect found on any of the objective or subjective metrics.

4 Results

For each metric, we conducted a one-way (technique) repeated-measures analysis of variance (ANOVA) at a 95% confidence level. If Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. Bonferroni post hoc tests were used to determine which pairs of conditions were significantly different.

4.1 Cognitive Load Metrics

We did not find any significant differences for *Accuracy*, $F(2, 58) = 1.287$, $p = 0.284$, or *Precision*, $F(2, 58) = 0.205$, $p = 0.815$. But a significant difference was found on *Recall*, $F(2, 58) = 13.630$, $p < 0.001$, and *F-measure*, $F(2, 58) = 6.767$, $p = 0.002$. For *Recall*, Walking-In-Place (M = 0.471, SD = 0.144) was significantly lower than Scaled Walking (M = 0.607, SD = 0.194) and Human Joystick (M = 0.592, SD = 0.163). For *F-measure*, Walking-In-Place (M = 0.527, SD = 0.120) was also significantly lower than Scaled Walking (M = 0.606, SD = 0.146) and Human Joystick (M = 0.617, SD = 0.138).

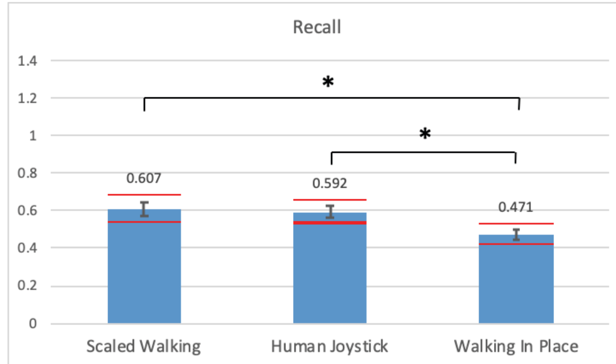

Figure 9: Mean results for Recall with standard error bars. Red lines represent 95% confidence intervals. Asterisks indicate significantly different techniques.

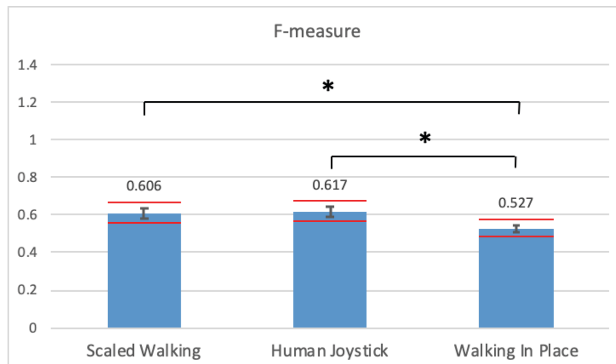

Figure 10: Mean results for F-measure with standard error bars. Red lines represent 95% confidence intervals. Asterisks indicate significantly different techniques.

4.2 Travel Time Metrics

A significant difference was found on the *Total Time* used to complete the task, $F(2, 58) = 23.926$, $p < 0.001$. The time used with Scaled Walking (M = 106.901, SD = 39.276) was significantly less than Walking-In-Place (M = 150.731, SD = 32.513) and Human Joystick (M = 157.548, SD = 44.307).

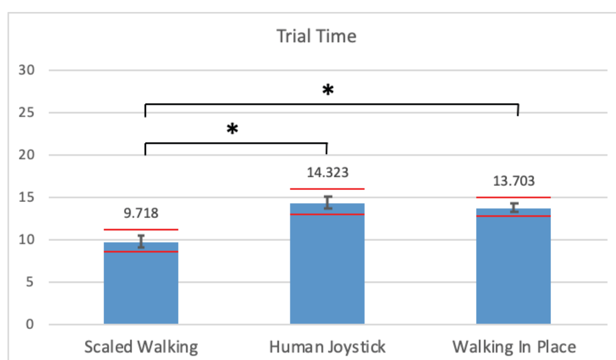

Figure 11: Mean results for Trial Time with standard error bars. Red lines represent 95% confidence intervals. Asterisks indicate significantly different techniques.

Among the sub-components of the *Total Time*, a significant difference was also found on *Ballistic Time*, *Refinement Time*, *Exit Time*, and *Trial Time*. For *Ballistic Time*, $F(2, 58) = 7.227$, $p = 0.002$, Human Joystick (M = 9.722, SD = 3.567) was significantly slower than Walking-In-Place (M = 7.611, SD = 1.977) and Scaled Walking (M = 7.801, SD = 3.443). For *Refinement Time*, F(1.253, 36.333) = 41.561, p < 0.001, Scaled Walking (M = 0.536, SD = 0.454) was significantly faster than Human Joystick (M = 2.523, SD = 0.899), which was significantly faster than Walking-In-Place (M = 3.899, SD = 2.202). For *Exit Time*, F(2, 58) = 31.530, p < 0.001, Scaled Walking (M = 1.381, SD = 0.418) required significantly less time than Human Joystick (M = 2.078, SD = 0.684) and Walking-In-Place (M = 2.193, SD = 0.726). For *Trial Time*, F(2, 58) = 23.926, p < 0.001, Scaled Walking (M = 9.718, SD = 3.571) required significantly less time than Human Joystick (M = 14.323, SD = 4.028) and Walking-In-Place (M = 13.703, SD = 2.956).

4.3 Simulator Sickness

For the *Total Simulator Sickness*, F(1.474, 42.734) = 8.039, p = 0.003, Human Joystick (M = 48.131, SD = 50.338) induced significantly more simulator sickness than Scaled Walking (M = 24.684, SD = 23.707) and Walking-In-Place (M = 34.159, SD = 35.829). Significant differences were also found on all the subcomponents of simulator sickness. For *Disorientation*, F(1.493, 43.289) = 7.725, p = 0.003, Human Joystick (M = 59.856, SD = 67.816) is significantly worse than Scaled Walking (M = 29.696, SD = 34.240) and Walking-In-Place (M = 38.512, SD = 50.080). For *Nausea*, F(1.440, 41.760) = 8.564, p = 0.002, Scaled Walking (M = 15.264, SD = 17.285) was significantly better than Walking-In-Place (M = 24.804, SD = 24.496) and Walking-In-Place was significantly better than Human Joystick (M = 36.252, SD = 39.247). For *Oculomotor*, F(2, 58) = 5.513, p = 0.006, Scaled Walking (M = 21.729, SD = 18.539) was significantly better than Walking-In-Place (M = 28.551, SD = 28.687) and Human Joystick (M = 36.131, SD = 36.362) was the worst among the three techniques.

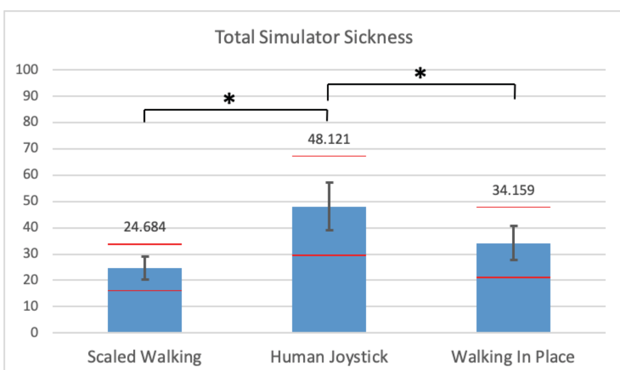

Figure 12: Mean results for Total Simulator Sickness with standard error bars. Red lines represent 95% confidence intervals. Asterisks indicate significantly different techniques.

4.4 Presence

For the *Overall Presence*, no significant difference was found, F(1.514, 43.918) = 1.263, p = 0.285. On each respective subcomponent, there was also no significant difference found on *Spatial Presence*, F(1.605, 46.532) = 1.241, p = 0.292, and *Involvement*, F(2, 58) = 0.302, p = 0.740. There was a significant difference found on *Experienced Realism*, F(2, 58) = 3.516, p = 0.036. Scaled Walking (M = 3.125, SD = 1.106) afforded significantly more realism than Human Joystick (M = 2.767, SD = 0.888) and Walking-In-Place (M = 2.650, SD = 1.104).

4.5 Perceived Usability

A significant difference was found on the *Perceived Usability*, F(2, 58) = 24.541, p < 0.001. Scaled Walking (M = 77.917, SD = 15.044) was found significantly better than Human Joystick (M = 59.667, SD = 23.228) and significantly better than Walking-In-Place (M = 49.417, SD = 20.560).

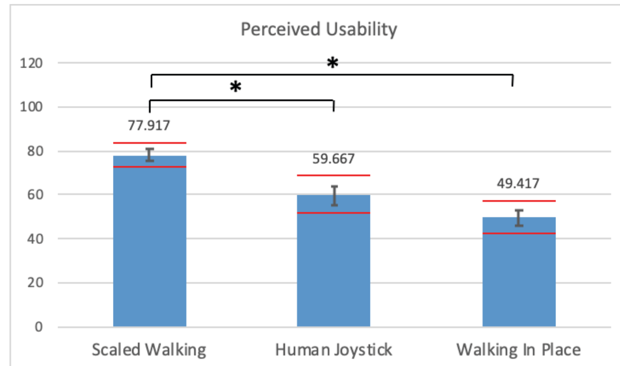

Figure 13: Mean results for Perceived Usability with standard error bars. Red lines represent 95% confidence intervals. Asterisks indicate significantly different techniques.

4.6 Exit Survey

In our exit survey, several subjective questions were asked to rate the three walking metaphors. For the question "Which technique were you able to control events better with?", 23 participants chose Scaled Walking while 4 chose Human Joystick and 3 chose Walking-In-Place. For the question "Which technique did your interactions with the environment seem more natural?", 24 participants chose Scaled Walking, 4 chose Walking-In-Place, and 2 chose Human Joystick. For the question "Which technique did your experiences in the virtual environment seem more consistent with your real-world experiences?", 25 participants chose Scaled Walking, 3 chose Walking-In-Place, and 2 chose Human Joystick. For the question "Which technique were you able to anticipate what would happen next in response to your actions better?", 19 participants chose Scaled Walking, 6 chose Human Joystick, and 5 chose Walking-In-Place.

5 Discussion

Below we discuss our results, their general implications, and the limitations of our study.

5.1 Scaled Walking Afforded the Best Travel

Many of our results indicate that Scaled Walking was the best walking metaphor for our travel task. It is important to note that these results likely cannot be generalized beyond the evaluated travel task, which limited travel distances to 10 meters. Also, our task involved initiating and terminating travel, in addition to continuing travel, unlike many prior studies.

Our results indicate the Scaled Walking required significantly less time than Human Joystick and Walking-In-Place, in terms of *Total Time*, *Refinement Time*, *Exit Time*, and *Trial Time*. Scaled Walking also required significantly less time than Human Joystick in terms of *Ballistic Time*. These results do not support our H2 hypothesis that Human Joystick would afford the fastest travel. Instead, they clearly indicate that Scaled Walking afforded the best performance for our travel task. One reason Human Joystick did not perform better in terms of travel time is that many of the participants decided to move much slower than expected with the technique, by stepping a short distance outside of the no-travel zone. We believed they chose to do this to reduce discomfort and maintain better control over stopping travel.

In addition to the travel times, Scaled Walking was the best walking metaphor in terms of *Perceived Usability*. On the SUS questionnaire, participants rated Scaled Walking significantly higher than Human Joystick and Walking-In-Place. Furthermore, according to the exit survey, Scaled Walking was undoubtedly considered the best technique by the participants, in terms of several aspects, including the ability to control events and natural interactions with the environment.

5.2 Walking-In-Place Required the Most Cognition

In terms of cognitive load, our results indicate that Scaled Walking and Human Joystick required significantly less cognitive load to use than Walking-In-Place. While we did not find any significant cognitive differences in terms of *Accuracy* and *Precision*, we found that Walking-In-Place required significantly more cognitive load than Scaled Walking and Human Joystick in terms of *Recall* and F-*measure*.

These results partially support our H1 hypothesis that Scaled Walking would require the least cognitive load. We most likely did not find any significant differences for Accuracy and Precision due to the large disproportion of non-match stimuli to match stimuli. As for the lack of significant differences between Scaled Walking and Human Joystick, we observed during the study that participants tended to travel slowly with Human Joystick, which allowed them to have more time between targets and focus more on the cognitive task.

One reason that we believe Walking-In-Place required the most cognitive load is because it involved the most uncommon motor actions. In our study, we allowed participants to choose between using a marching or tapping gesture to activate Walking-In-Place. Marching is not a common motor action for most people, outside of military or marching bands. On the other hand, while Nilsson et al. [38] suggest that the biomechanics of the tapping gesture are more similar to the biomechanics of real walking, the kinematics of the tapping gesture are clearly different, as seen in Figure 7. Hence, Walking-In-Place does involve uncommon motor actions. On the other hand, Scaled Walking involves essentially the exact same kinematics and kinetics as real walking, and Human Joystick involves the common motor action of stepping outward (though stepping back into the no-travel zone is a bit uncommon).

5.3 Human Joystick Induced the Most Sickness

Our results indicate that Human Joystick induced significantly more simulator sickness than Scaled Walking and Walking-In-Place, in terms of *Total Simulator Sickness*, *Disorientation*, *Nausea*, and *Oculomotor*. Our results also indicate that Walking-In-Place induced more *Nausea* and *Oculomotor* discomfort than Scaled Walking. These results partially support our H3 hypothesis that Scaled Walking would induce the least simulator sickness.

We believe that Human Joystick induced the most simulator sickness due to involving the largest discrepancies between visual and vestibular motion cues, which are believed to cause simulator sickness, according to the sensory conflict theory [24]. After activating travel, which does not involve many conflicts, Human Joystick often involves the participant standing outside of the no-travel zone while continuing travel. Hence, the participant's visual system is perceiving motion cues while the vestibular system is not perceiving any cues. In contrast, Walking-In-Place involves the participant stepping to activate travel, which generates both visual and vestibular cues of movement. However, it is important to note that due to our expected stance height threshold, there was a small amount of latency between the immediate vestibular cues and the resulting visual cues. This helps to explain why Walking-In-Place induced more discomforts than Scaled Walking.

5.4 The Uncanny Valley of Interaction Fidelity

One potential explanation for our results indicating that Scaled Walking was overall the best walking metaphor is the uncanny valley of interaction fidelity [32]. McMahan [29] first used the term "uncanny valley" with regard to VR interactions to refer to his observations that mid-fidelity interaction techniques performed significantly worse than high-fidelity and low-fidelity interaction techniques. This phenomenon has also been observed by Marsh et al. [28] and Nabiyouni et al. [37]. McMahan et al. [32] have compiled several research studies that demonstrate it.

By using the Framework for Interaction Fidelity Analysis (FIFA) [29, 32], it is clear that Scaled Walking affords a very high level of interaction fidelity to real walking, as it is a full-gait walking metaphor. The only difference is its control symmetry due to scaling the user's movements. On the other hand, Human Joystick and Walking-In-Place are both mid-fidelity, partial-gait walking metaphors that differ from real walking in terms of kinematics, kinetics, and control symmetry. Hence, considering that Human Joystick and Walking-In-Place are much lower fidelity, our results that Scaled Walking is the better walking metaphor is not too surprising.

5.5 Limitations of Our Study

While our results indicate that Scaled Walking was the better walking metaphor, it is important to note that our results should not be generalized beyond our travel task. Specifically, our travel task involved moving between virtual targets located 10 meters apart. For larger distances, which are common in many virtual environments, Scaled Walking is less likely to perform well due to requiring a lower control-display ratio in order to fit the larger environment within the physical tracking space. Therefore, future research involving more-complex travel scenarios and longer trajectories is required to better understand our results.

Another limitation of our study is that our results are dependent upon the travel speeds that we implemented for the techniques. As discussed, we had to use a travel speed greater than human walking, in order to investigate Scaled Walking, which also required greater speeds for Human Joystick and Walking-In-Place to obtain comparable results. These higher travel speeds likely affected our cognitive load metrics and our simulator sickness results. Hence, more research investigating different travel speeds, including variable speeds, is needed to validate our current results.

6 Conclusion

In this paper, we used a dual-task, travel-cognitive methodology to investigate and compare three walking metaphors suitable for consumer VR systems: Scaled Walking, Human Joystick, and Walking-In-Place. Using this methodology, we conducted a user study to investigate the cognitive load, travel times, simulator sickness, presence, and perceived usability of the three walking metaphors. Our results indicate the Scaled Walking afforded the best overall travel performance and usability, while Walking-In-Place required significantly more cognitive load to use and Human Joystick induced significantly more simulator sickness. These results are closely related to the fact that Scaled Walking is a high-fidelity, full-gait walking metaphor while Human Joystick and Walking-In-Place are lower-fidelity, partial-gait techniques.

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