I'm a Giant: Walking in Large Virtual Environments at High Speed Gains

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Figure 1: Left) Average human-size avatar walking in a large virtual city. Middle) Ground-Level Scaling technique used to achieve a 10x speed gain. Right) Eye-Level Scaling used to achieve a 10x speed gain, while maintaining a street-level view.

ABSTRACT

Advances in tracking technology and wireless headsets enable walking as a means of locomotion in Virtual Reality. When exploring virtual environments larger than room-scale, it is often desirable to increase users' perceived walking speed, for which we investigate three methods. (1) *Ground-Level Scaling* increases users' avatar size, allowing them to walk farther. (2) *Eye-Level Scaling* enables users to walk through a World in Miniature, while maintaining a street-level view. (3) *Seven-League Boots* amplifies users' movements along their walking path. We conduct a study comparing these methods and find that users feel most embodied using Ground-Level Scaling and consequently increase their stride length. Using Seven-League Boots, unlike the other two methods, diminishes positional accuracy at high gains, and users modify their walking behavior to compensate for the lack of control. We conclude with a discussion on each technique's strength and weaknesses and the types of situation they might be appropriate for.

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CCS CONCEPTS

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

KEYWORDS

Virtual Reality, Locomotion, Walking Speed, Translational Gain, Seven-League Boots, World in Miniuature, Body Scale

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1 INTRODUCTION

With the release of untethered head-mounted displays and advances in tracking technology users can physically walk around to explore room-scale Virtual Reality (VR) applications. Walking is a familiar mechanism that unlike some locomotion techniques, including teleportation [7], walk in place [23], or omni-directional treadmills [8], does not require training or additional hardware and does not hinder users' spatial awareness.

Virtual Reality offers many opportunities that go beyond the attempt to closely replicate the experience of reality. In a virtual environment, we can create magical experiences that are simply impossible in the real world [10]. With regards to walking, we could significantly increase users' perceived walking speed in VR. Large speed gains in VR:

- Allow rapid and efficient exploration of large virtual environments.
- Enable users to travel farther in the virtual scene to overcome the constraints of their physical space.
- Create flexible mappings between the virtual content and physical props.

To increase the users' perceived walking speed, a simple solution is to amplify movements along the horizontal plane [34]. However, only small gains are achievable in practice without diminishing users' control accuracy [35]. Seven-League Boots is a variation of this approach that only amplifies movements along the user's walking path, without amplifying side-to-side head sways that naturally occur while walking [14]. In practice, it is challenging to reliably predict users' intended walking direction, as a result Seven-League Boots is not commonly used.

We explore two alternative approaches based on scale change for walking at high speed gains in large virtual environments. We hypothesize that at high gains, scaling might perform better, as it maintains a 1:1 mapping between the user's movements and the movements of the virtual camera. The first technique, *Ground-Level Scaling*, in effect increases the users' avatar size, allowing them to walk farther in the virtual environment with each step. In our experimentation we found that due to the drastic shift in eye level, the details of the virtual scene are often missed when using Ground-Level Scaling with large gains. To address this limitation, we explore a second alternative, *Eye-Level Scaling*, that enables users to walk through a World in Miniature, while maintaining a street-level view.

We conducted a user study comparing Ground-Level Scaling and Eye-Level Scaling to an improved version of the Seven-League Boots at speed gains of $3x$, $10x$, and $30x$. During the evaluation, users were directed to walk to different targets in a virtual city, while optimizing for both time and accuracy.

Participants overall preferred the Ground-Level Scaling technique for walking around in a large virtual environment. For the interactive task at a gain of $30x$, participants found the two scale change methods more preferable and comfortable than the Seven-League Boots and felt most embodied in Ground-Level Scaling. Moreover, similar to prior work on 2D Translational Gains [35], we found that when using Seven-League Boots, control accuracy diminishes at high gains. Interestingly, participants modify their walking behavior to compensate for this lack of accuracy. We conclude with a discussion on the strength and weaknesses of each technique. We anticipate that changes in walking behavior that emerge with the use of each technique, including the changes in stride length and walking speed, will also impact the types of VR scenarios that they will be appropriate for.

2 RELATED WORK

Locomotion Taxonomy

Nilsson's taxonomy [22] classifies virtual locomotion techniques based on three orthogonal dimensions: virtual movement source, user mobility, and metaphor plausibility, as shown in Figure 2. In this paper, the locomotion techniques of interest lie at the intersection of body-centric, mobile, and magical categories. These techniques allow users to walk in VR, without the need for training or additional hardware, while experiencing an outcome that is not plausible in the real world.

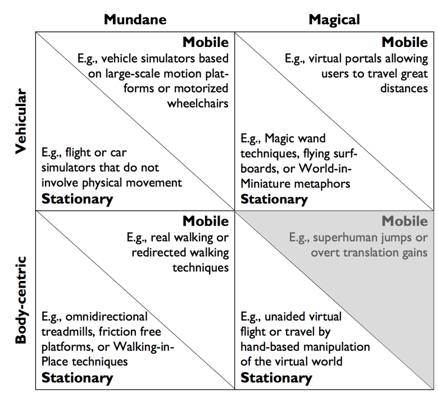

Figure 2: Taxonomy of virtual travel techniques presented by Nilsson [22]. The methods explored are in the highlighted category of body-centric, mobile, and magical.

Speed Gain Techniques

Most body-centric, mobile, and magical locomotion techniques, such as Superhuman Jumps, 2D Translational Gain, and Seven-League Boots, aim to increase users' perceived walking speed in Virtual Reality.

Superhuman Jumps. This technique predicts users' destination and allows them to virtually jump to that location [5]. During the jump a fast and blurred animation of the path from the users' current location to their destination is shown. Using Superhuman Jumps users can travel large virtual distances, while walking short paths in the real world.

2D Translational Gain. This technique amplifies users' movements along the horizontal plane. Prior research has studied subtle speed gains with 2D Translational Gain that are unnoticeable by users. Steinicke et al. found that speed gains of up to $1.26x$ remained unnoticed by participants [27]. However, in this work we are interested in high speed gains that are certainly noticeable and create a magical virtual experience. Williams et al. have studied speed gains up to $10x$ using 2D Translational Gain [34]. It has also been shown that in an interactive room-scale virtual environment, when using this technique, positional accuracy diminishes at gains beyond $2x$ [35]. This shortcoming motivates the need for alternative approaches for increasing users' virtual walking speed.

Seven-League Boots. This technique is a variation on 2D Translational Gain that amplifies movements along the users' walking direction, without amplifying the sideways movements that naturally occur when walking [14]. Interrante et al. have shown that users maintain better spatial awareness when using Seven-League Boots, compared to flying with a magic wand [13]. Moreover, they have found that users overwhelmingly prefer Seven-League Boots to 2D Translational Gain [14]. However, due to the challenge of reliably predicting users' intended walking direction, 2D Translational Gain is more commonly used in practice. In this work, we show that when using Seven-League Boots, similar to 2D Translational Gain, positional accuracy diminishes at high speed gains. We explore two alternative techniques based on scale changes for achieving high speed gains in VR, and compare these techniques to Seven-League Boots.

Scale Change in Virtual Reality

Scale change in VR has been explored for a variety of applications. Modifying the scale of the virtual environment allows users to view virtual components from different perspectives and learn about their inherent hierarchical structures [1]. In the educational domain, multi-scale virtual environments have been utilized to teach concepts related to astronomy [33], anatomy [18], and molecular chemistry [9]. In 3D CAD tools, scale change enables users to complete detailed tasks with a degree of precision that otherwise would not be possible. For example, in the MakeVR CAD tool [15] with two-handed gestures, users can increase the size of their virtual model relative to their avatar to work on small details.

Scale change has been used for navigation in virtual environments. Word in Miniature (WIM) is a user interface technique that provides a hand-held miniature copy of the virtual environment [29]. Using this third-person view, users can directly manipulate objects and navigate to specific locations by flying into the WIM [25]. The scaling techniques used in this paper, similar to prior work [19, 21], allow users to walk through a WIM from a first-person perspective. In Eye-Level Scaling the virtual world is miniaturized, raised up to maintain users' eye level, and locked in place such that they can walk around and explore the scene. Prior research has also investigated multi-scale travelling on 3D desktop environments [36] and found that scale changes during travel are ineffective. Based on this finding, we also utilize a scale-then-travel technique, in which scale changes occur prior to walking and when the user is stationary.

3 LARGE SPEED GAIN LOCOMOTION METHODS

We explore three techniques for walking at high speed gains in large virtual environments: Ground-Level Scaling, Eye-Level Scaling, and an improved version of the Seven-League Boots [14].

Ground-Level Scaling

Ground-Level Scaling increases the size of the users' avatar relative to the virtual environment, allowing them to walk farther. To implement this technique, the virtual world is scaled down with the center of scaling at the midpoint between the user's feet. This center of scaling, shown in Figure 3, is critical for creating the illusion of becoming a giant; however, other factors also play a role [20].

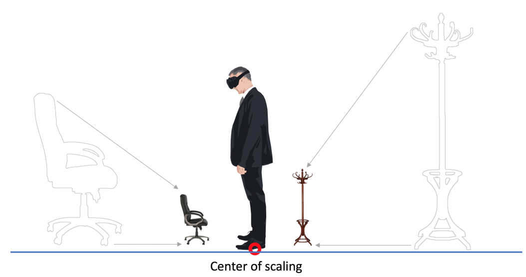

Figure 3: To create the illusion of Ground-Level Scaling, the center of scaling is the midpoint between the user's feet.

Based on the findings of prior multi-scale traveling research [36], we only activate the scale change when users are stationary. Moreover, the scale change happens instantaneously, as we found during our experimentation that animating the transition is likely to result in simulation sickness. The field of view in this mode is shown in Figure 4.

Figure 4: Left) View without any speed gain at 1x. Right) View when using Ground-Level Scaling at 30x.

Eye-Level Scaling

When using the Ground-Level Scaling technique often the details of the virtual scene are missed as a result of the drastic shift in eye level. To address this limitation, we explore an alternative technique, Eye-Level Scaling, that enables users to walk through a World in Miniature, while maintaining their eye level. To implement this technique, the virtual world is scaled down with the center of scaling at the midpoint between the user's eyes. This center of scaling, shown in Figure 5, creates the illusion that the user is walking through a miniature world that has been placed at their eye level.

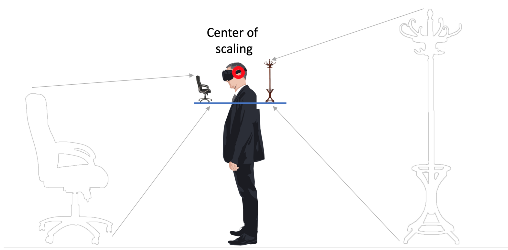

Figure 5: In Eye-Level Scaling, the center of scaling is the midpoint between the user's eyes.

When using the Eye-Level Scaling technique, users maintain their eye level. However, as a consequence of the scaling, their virtual view changes at different speed gains. Figure 6 shows the stereo views when using this method at speed gains of $3x$, $10x$, and $30x$. Note that a similar scaling effect can be perceived by modifying the Virtual Interpupillary Distance, also known as the Virtual Camera Separation.

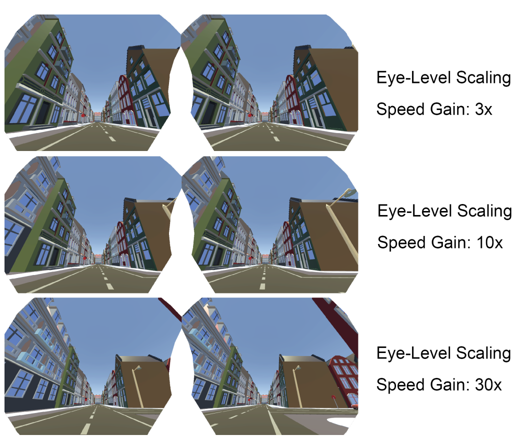

Figure 6: Eye-Level Scaling stereo views at different gains.

Similar to Ground-Level Scaling, Eye-Level Scaling transitions happen instantaneously and only when users are stationary. The field of view when using this technique is shown in Figure 7. In first-person VR applications, users will not be able to see their avatar as they walk through the WIM.

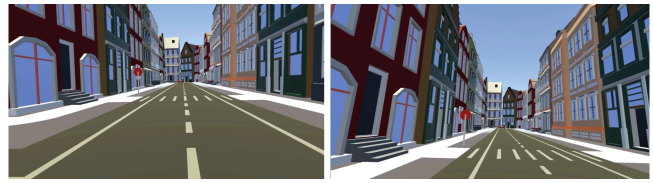

Figure 7: Left) View without any speed gain at 1x. Right) View when using Eye-Level Scaling at 30x.

Seven-League Boots

To draw comparisons between the described methods and a baseline, we implemented the Seven-League Boots technique that amplifies users' movements along their walking path [14]. This is done by taking the users' displacement at every frame, projecting it on their walking path, multiplying that projection by the gain, and shifting the camera rig by that amount. Note that unlike the other two methods, the Seven-League Boots does not require any scale changes. To ensure that the best level of performance can be achieved using this technique, instead of supporting free exploration, we restricted the VR experience to a target following task. This constraint ensures that we can accurately determine the user's walking path at all times and only amplify the movements projected along this path. Moreover, once users reach the target we can turn off the boots such that their movements are not amplified when they rotate in place.

The Seven-League Boots metaphor aims to create the illusion that every step is longer in the virtual world. This illusion breaks when users move their head in the direction of the walking path and these movements get amplified even though they are stationary. To mitigate this effect, we used foot tracking to detect when users are walking, and turned off the boots when users are stationary. Overall, we found that these constraints and modifications considerably improved the user's experience of the Seven-League Boots technique. However, note that the findings in this paper are influenced by these modifications.

Method Comparisons

Figure 8 shows the stereo view of a stationary user, for each technique at $30x$ speed gain. In the Seven-League Boots, the stereo view when stationary is identical to that of Normal Walking at $1x$, as no scaling is applied to the virtual scene. When walking, users' head movements are only amplified along their predetermined walking path, by shifting the camera rig. In Eye-Level Scaling, the users maintain their eye level and can perceive the scaling effect even when stationary. When walking, users' head movements appear amplified in all directions due to the isometric scaling. In Ground-Level Scaling, a similar effect to Eye-Level Scaling is achieved, with the addition of an upward shift in eye level.

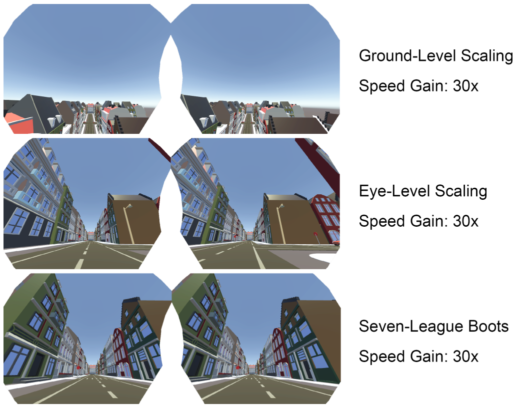

Figure 8: Stereo views for all methods at speed gain of 30x.

4 USER EVALUATION

We conducted a user-evaluation and compared Ground-Level Scaling, Eye-Level Scaling, and Seven-League Boots locomotion techniques, at speed gains of $3x$, $10x$, and $30x$.

Participants

We recruited 18 participants (5 female and 13 male), ages 18-65 (mean = 22), from our institution. All participants had normal or corrected-to-normal stereo vision and had experienced Virtual Reality prior to the experiment. 7 participants were non-gamers, 9 casual gamers, and 3 core gamers. Each participant received a $50 gift card for an hour of their time.

Experimental Setup

The study took place in a $2.8m$ x $4m$ x $2.8m$ room. To enable untethered walking in Virtual Reality, we used the HTC Vive head-mounted display [32] along with the TPCAST Wireless Adpater [31]. HTC Vive lighthouses were mounted on the opposite corners of the ceiling, $4.8m$ apart. The TPCAST TX Module transmitter was installed next to one of the lighthouses. Participants wore the battery pack around their waist and held two HTC Vive controllers in their hands, as shown in Figure 9. We asked participants to wear closed-toe shoes prior to the experiment. Two HTC Vive trackers were attached to the participant's shoes using a buckled elastic strap. We hung matte wallpapers on the walls to eliminate glare from the glass windows and to improve tracking.

To simulate a large virtual environment, we utilized the Low poly European City Pack in Unity 3D game engine. For the target following task, we rendered a green X mark on the ground and an arrow positioned at the participant's eye-height, shown on the left in Figure 9. As participants are unable to see their virtual representation in Eye-Level Scaling, the avatar was invisible in all conditions, which is consistent with most first-person VR applications.

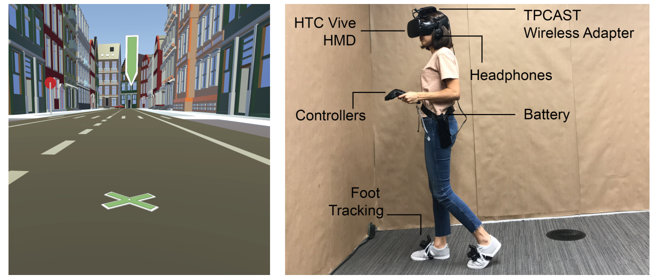

Figure 9: Left) Target shown in the virtual city. Right) Participant wearing the wireless HMD and feet trackers while holding the hand controllers.

Procedure

During the study participants performed a target following task. They were asked to walk towards the green target, while optimizing for both time and speed. They were then asked to pull the trigger on their right-hand controller to indicate that they have reached the target. The target would then disappear and appear in another location, providing participants with a path to walk on while remaining within the boundaries of the physical room. The position of the targets were generated randomly within the physical room, with no consecutive targets less than $1.5m$ apart.

A training session was first conducted to familiarize users with the virtual scene and the target following task. Then users performed the target following task for $1min$ without any speed gain. During this one-minute baseline condition, the position of the foot trackers and hand controllers, as well as the position and orientation of the headset were recorded. The following sequence was repeated 9 times, as a combination of three locomotion techniques (Ground-Level Scaling, Eye-Level Scaling, Seven-League Boots) with three speed gains ($3x$, $10x$, $30x$):

(1) Target following task for $30sec$ at $1x$: to reset from the previous sequence and to create a baseline, users always began by following the targets without any speed gain.
(2) Target following task for $30sec$ with speed gain: to allow users to explore and get familiar with the locomotion technique at this particular speed gain.
(3) Target following recording for $1min$ with speed gain: to record data from trackers, hand controllers, and the headset during a one-minute window.

Note that in Ground-Level Scaling and Eye-Level Scaling, to achieve the speed gains of $3x$, $10x$, and $30x$ the virtual scene was simply scaled to $1/3rd$, $1/10th$, and $1/30th$ of the size of the original scene. All locomotion techniques were activated by the experimenter, and participants were given a three-second countdown. For each locomotion technique, participants first experienced a speed gain of $3x$, followed by $10x$ and $30x$, such that they could gradually acclimate to large speed gains. After the target following task at $30x$, participants filled a post-task questionnaire with 13 questions, shown in Table 1. Q1-3 were aimed at probing users' preferences, stability, and comfort in VR. Q4-7 were chosen from the Standard Embodiment Questionnaire [11]. Q8-13 targeted task performance and were extracted from NASA TLX questionnaire [12]. Participants responded to each statement on a Likert-Scale from 1 (I strongly disagree) to 5 (I strongly agree).

Balanced Latin-Square was used to determine the order of the locomotion techniques for each participant. At the end of the user study, participants completed a post-study questionnaire commenting on their overall experience and their preferred technique for walking in large virtual environments. The Simulation Sickness Questionnaire (SSQ) [17] was used before and after the one-hour experiment. All sessions were audio and video recorded.

Questionnaire Results

The results of the post-task questionnaire and the Friedman's ANOVA are summarized in Table 1. All data and calculations can be found in a public Jupyter notebook[1].

Principal Component Analysis. To analyze the post-task questionnaire results, we conducted a Principal Component Analysis (PCA) on the 13 questions to detect the main factors explored by the questionnaire [16]. PCA analysis in effect calculates loadings for more relevant questions that have greater variability among participants, and clusters them based on their algebraic alignment. [4, 11, 16].

The factors that emerged from the PCA on the questionnaire responses were selected using the Kaiser criterion. The Kaiser-Meyer-Olkin measure verified the sampling adequacy for the analysis, indicating that all the questions correlated reasonably well with all others, and none of the correlation coefficients were excessively large (KMO = 0.88, and all the KMO values for individual items were above the acceptable limit of 0.5, Bartlett's test of sphericity, $\chi^2(78) = 500, p < 0.001$) [16]. An initial analysis was run to obtain eigenvalues for each component in the data. Two components had eigenvalues over Kaiser's criterion of 1 and in combination explained 57% of the variance.

The post-task questionnaire responses were clustered into two factors (loadings are summarized in Table 1). Note that the first factor combines the Preference Questions (Q1-3) and NASA TLX Questions (Q8-13). Interestingly, the second factor is the Embodiment Questions (Q4-7) with the addition of the physical demand question from NASA TLX (Q9).

[1]User study questionnaire data and calculations can be found at https://notebooks.azure.com/parastooabtahi/projects/Im-a-Giant

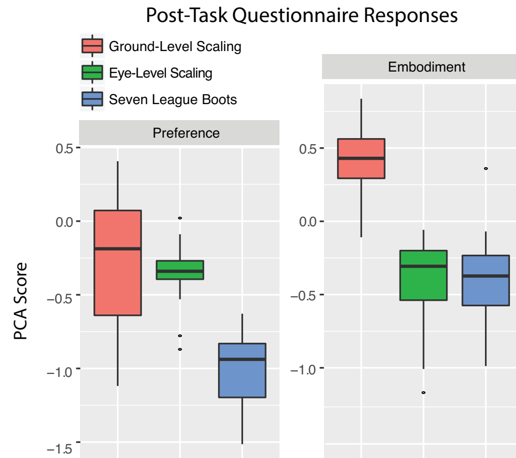

Figure 10: Preference and Embodiment are the two main factors that emerge from clustering of the post-task questionnaire responses using PCA.

Planned comparisons between the different conditions in each experiment were carried out using non-parametric within-subjects paired Friedman test, as shown in Figure 10. The results show that high speed gains were less preferred (F1) in the Seven-League Boots (Friedman $\chi^2 = 19, df = 2, p - value = 7.485e - 05$), and there was no significant difference between the Eye-Level Scaling and Ground-Level Scaling conditions. Moreover, the embodiment factor (F2) was significantly higher in the Ground-Level Scaling condition (Friedman $\chi^2 = 28, df = 2, p - value = 8.315e - 07$) and no significant differences were found between the Seven-League Boots and the Eye-Level Scaling conditions.

Simulation Sickness. The average SSQ score was 0.833 ± 1.15 before the experiment and 5.78 ± 5.93 after. Previous studies have found that with scores lower than 12, Simulator Sickness can be almost neglected with a 0% dropout rate [2].

Qualitative Results

At the end of the experiment, participants were asked to choose their preferred locomotion technique for walking in large virtual environments, and to reason their selection. 12 participants chose Ground-Level Scaling, 3 Eye-Level Scaling, and 3 Seven-League Boots. Participants said they liked Ground-Level Scaling because they felt most in control ($x7$), and it was more natural ($x4$), more comfortable ($x4$), less sickening ($x2$), less disorienting ($x2$), and it met their expectations ($x1$), was easy to use ($x1$), and offered a good overview of the virtual scene ($x1$). Regarding Eye-Level Scaling, P4 said "I didn't like that the virtual ground was at chest or neck level". P9 mentioned that it "felt strange since it felt like my body was missing, slightly suffocating". This criticism perhaps could be related to the lack of embodiment in this mode, as P13 pointed that they were "not feeling like [they were]

Table 1: Post-Task Questionnaire Results and Factor Loadings

	Factor Loadings		Average Scores ± SD			
Questions	Prefer (F1)	Embody (F2)	Ground-Level Scaling (GL)	Eye-Level Scaling (EL)	7-League Boots (7LB)	Friedman p<0.05
Q1: I liked walking around in this mode.	0.655		4.2±0.9	2.8±1.3	2.8 ± 1.5	GL vs 7LB & EL
Q2: I felt unstable walking around in this mode.	-0.685		2.1±1.3	2.4±1.5	3.6 ± 1.2	GL vs 7LB
Q3: I felt discomfort and motion sickness when walking around in this mode.	-0.774		1.6±1.0	2.2±1.4	2.9 ± 1.4	GL vs 7LB
Q4: The movement of the virtual body were caused by my movement.		0.739	4.7±0.7	4.6±0.9	3.8 ± 1.1	GL vs 7LB
Q5: I felt like I could control the virtual body as if it was my own body.		0.716	4.6±0.8	4.2±1.2	2.6 ± 1.3	7LB vs GL & EL
Q6: I felt as if the virtual body was moving by itself.		-0.895	1.3±1.0	1.7±1.1	2.8 ± 1.2	GL vs 7LB
Q7: I felt as if the movements of the virtual body were influencing my own movements		-0.895	2.2±1.5	2.3±1.5	3.8 ± 1.1	7LB vs GL & EL
Q8: The task was mentally demanding	-0.567		1.6±0.8	1.7±1.0	2.9 ± 1.2	7LB vs GL & EL
Q9: The task was physically demanding.		-0.503	1.5±0.9	1.7±1.2	2.3 ± 1.0	GL vs 7LB
Q10: The pace of the task felt hurried or rushed.	-0.502		1.3±0.6	1.7±1.0	2.6 ± 1.5	GL vs 7LB
Q11: I was successful at accomplishing what I was asked to do.			4.7±0.5	4.7±0.6	3.4 ± 1.2	7LB vs GL & EL
Q12: I had to work hard to accomplish what I was asked to do.	-0.850		1.7±1.1	2.1±1.3	2.9 ± 1.5	GL vs 7LB
Q13: I felt insecure, discouraged, irritated, stressed, and annoyed.	-0.988		1.3±0.9	1.6±1.0	2.2 ± 1.3	

in a human body anymore". Future work should explore a center of scaling slightly lower than the eyes to mitigate this problem, particularly at high gains. Regarding Seven-League Boots, P18 said "I would step too far or not enough and lose track of where it was, and would keep trying to correct and adjust to get on the right spot." and P4 mentioned that it felt "Disorienting and difficult to be accurate".

Movement Analysis Results

To perform a thorough behavioral analysis we extracted several metrics from the foot tracking position data, shown in Figure 11, including step length, duration, and speed as well as positional accuracy at each target. By inspecting Figure 11, the differences between normal walking and walking using the Seven-League Boots at $10x$ speed gain become immediately evident, including the difference in regularity of feet movement, the number of reached targets, duration of pauses, and stride length. In the following sections, we analyze these differences in task performance and walking behavior.

Position Control & Accuracy. To measure accuracy during the target following task, we calculated the target error which is the Euclidean distance from the target to the midpoint between participants' feet, at instances when the right-hand trigger was pressed. The results are shown in Figure 12. We used a repeated measures ANOVA on the error with two factors: Gain ($3x$, $10x$, $30x$) x Condition (GL, EL, 7LB). There was a significant effect of Gain ($F(2, 34) = 4.4, p < 0.001$) and Condition ($F(2, 34) = 9.8, p < 0.01$), as well as an interaction between Gain and Condition ($F(4, 68) = 4.5, p < 0.003$).

We ran post-hoc comparisons with Bonferroni adjustments. There were no significant differences in target error between the two scale change methods and Normal walking: (GL error = $0.12 \pm 0.06m$, EL error = $0.08 \pm 0.05m$, and Normal walking error = $0.09 \pm 0.05m$). However, there were significant differences in target error between the scale change methods and the Seven-League Boots for all speed gains: $3x$ ($F(3, 68) > 4.72, p < 0.005$), $10x$ ($F(3, 68) > 31.72, p < 0.001$), and $30x$ ($F(3, 68) > 6.16, p < 0.001$). With errors ranging from $0.3 \pm 0.15m$ at gain of $10x$ to $0.86 \pm 1.31m$ at gain of $30x$, which in effect is 9 times larger than the target error

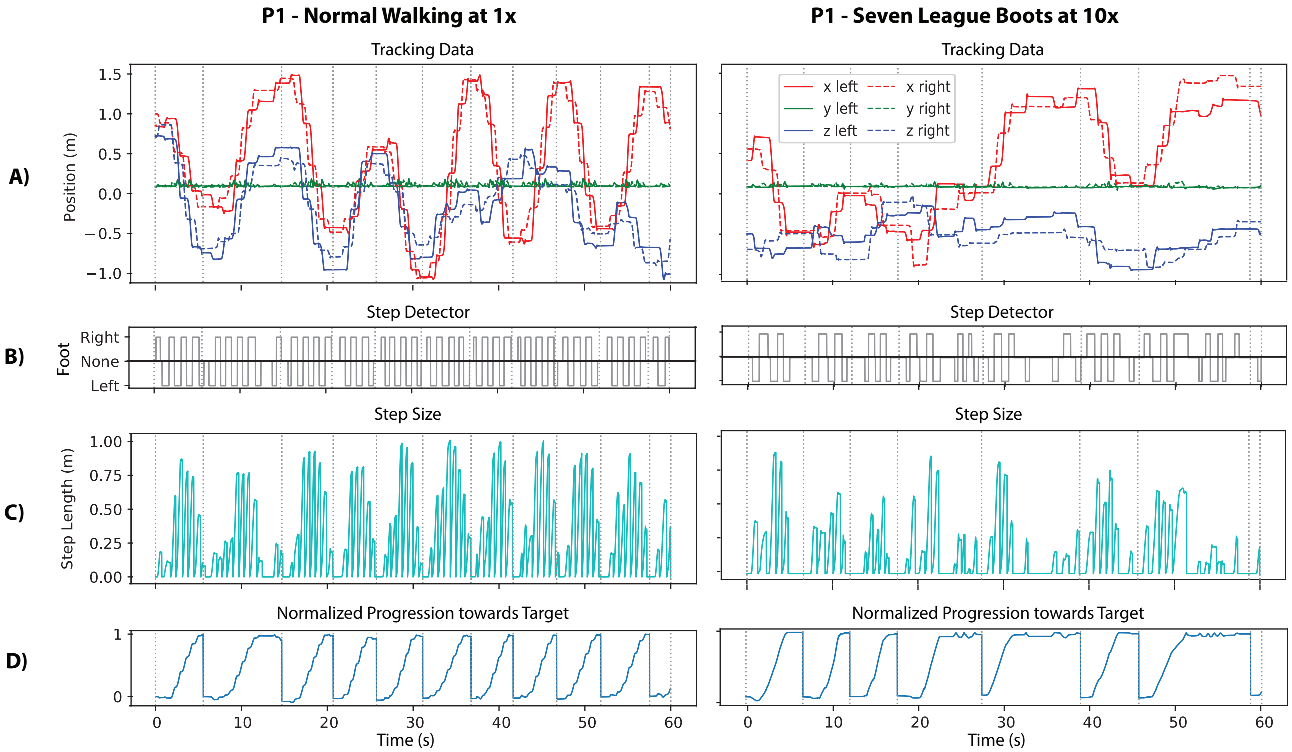

Figure 11: Excerpt of P1's behavioral data comparing normal walking at 1x and Seven-League Boots at 10x. A) Feet tracking x, y (up), z position with target position changes shown as vertical lines. B) Step Detection based on feet movement. C) Step Size: distance travelled since the start of the step. D) Normalized progression towards the target.

for Normal walking. Furthermore, there was a significant Pearson Correlation (Gain x Error) for the Seven-League Boots ($cor = 0.35$, $t = 2.72$, $df = 52$, $p = 0.008$, 95% $C.I.$ $[0.094, 0.56]$). Analysis with regards to demographics revealed that core gamers had significantly lower position errors (Pearson Correlation: $cor = -0.16$, $p = 0.031$, $t = -2.16$, $df = 17$, 95% $C.I.$ $[-0.29, -0.01]$).

The median normalized trajectory that participants followed from target to target is shown in Figure 13. To compare the trajectory curves we implemented a kernel density estimate (KDE) comparison procedure, using the SM library in R. KDE is a non-parametric procedure that produces a smooth estimate and compares the area between the curves using kernel analysis [6]. A significant difference was found at speed gain of $30x$ using Seven-League Boots ($p < 0.05$), an example of which can be observed in Figure 11D. Using the Seven-League Boots, participants approach the target much more rapidly; however, the trajectory plateaus near the end. This shows that after reaching the vicinity of the target, participants took multiple smaller steps while struggling to position themselves accurately at the target. Despite these efforts, as shown in Figure 12, positional accuracy was significantly lower when using Seven-League Boots.

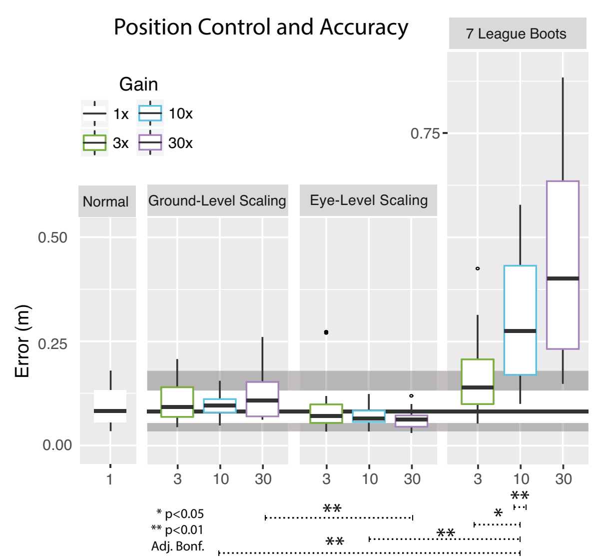

Figure 12: Distance to target boxplots, using median, 25th, and 75th percentiles. The whiskers extend up to 1.5 times the interquartile range from the edges of the box, to the furthest datum within that distance, and data points beyond that are represented as individual outlier points [6].

Step Analysis. We detect steps by analyzing the velocity of the right and left foot. We find step detection based on foot position to be inaccurate, perhaps due to a combination of users dragging their feet on the ground and the trackers randomly shifting on the users' shoes. We discard shorter steps at the beginning of the walking path from target-to-target, as they represent rotations in-place. We also discard the last step users took to reach the target, as these steps are modified for accurate positioning at the target and do not represent walking behavior. On average, participants took 11 steps to reach a target (Normal walking $\mu = 14$, $sd = 4.6$; Ground-Level Scaling $\mu = 12$, $sd = 2.5$; Eye-Level Scaling $\mu = 12.7$, $sd = 2.59$; Seven-League Boots $\mu = 10.1$, $sd = 3.7$). Approximately 2 steps were discarded in each target-to-target path.

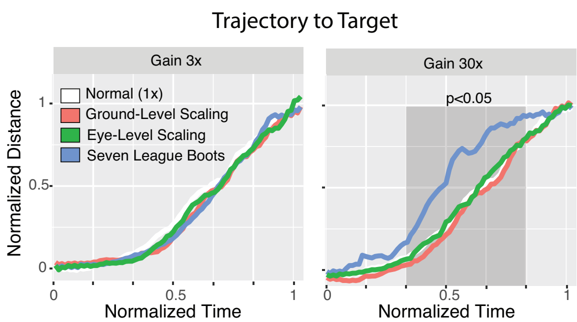

Figure 13: Median normalized trajectory from target to target. Highlighted area shows significant differences [6].

Step Size. In each condition, we calculated the participants' average stride length (Figure 14). We used a repeated measures ANOVA on the stride length with two factors: Gain ($3x$, $10x$, $30x$) x Condition (GL, EL, 7LB). We found a significant effect of Gain ($F(2, 34) = 6.6$, $p = 0.003$) and Condition ($F(2, 34) = 449.4$, $p < 0.001$) as well as an interaction between Gain and Condition ($F(4, 68) = 14.2$, $p < 0.001$). We ran post-hoc comparisons with Bonferroni adjustments. Participants in the Seven-League Boots significantly reduced their stride length compared to the two scale methods and also normal walking ($F(3, 68) = 25$, $p < 0.001$), with a 45% reduction from an average length of $0.7 \pm 0.14m$ to $0.38 \pm 0.13m$. This effect was more pronounced at larger speed gains (Pearson Correlation: $cor = -0.44$, $t = -3.58$, $df = 52$, $p = 0.0007$, 95% $C.I.$ $[-0.63, -0.2]$), with a 55% reduction to $0.31 \pm 0.11m$. We also found that when using the Ground-Level Scaling technique, participants increased their stride length up to 12% compared to walking at $1x$ ($F(3, 68) = 52$, $p = 0.006$), with a $0.79 \pm 0.1m$ stride at $30x$. In Ground-Level Scaling, participants who embodied the giant avatar increased their stride length more significantly (Pearson Correlation (Gain x Embodiment) $cor = 0.44$, $t = 3.58$, $df = 52$, $p = 0.0008$, 95% $C.I.$ $[0.2, 0.63]$).

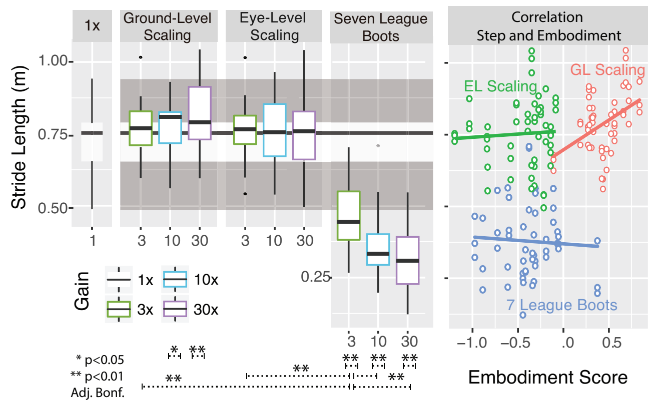

Figure 14: Stride Length boxplots and correlation of Stride Length and Embodiment per condition.

Average Step Velocity. In addition to taking smaller steps, in the Seven-League Boots, the average velocity per step was also lower, shown in Figure 15. We used a repeated measures ANOVA on the step speed, with two factors: Gain ($3x$, $10x$, $30x$) x Condition (GL, EL, 7LB). We found a significant effect of Gain ($F(2, 34) = 11.6$, $p < 0.001$) and Condition ($F(2, 34) = 65$, $p < 0.001$) as well as an interaction between Gain and Condition ($F(4, 68) = 20$, $p < 0.001$). We ran post-hoc comparisons with Bonferroni adjustments. Step speed in the Seven-League Boots at $3x$ was not significantly different. However, at larger gains participants became significantly slower ($F(3, 68) = 10$, $p < 0.001$); in fact, the average step velocity was negatively correlated with the gain (Pearson Correlation (Step Speed x Gain) $cor = -0.49$, $t = -4.1$, $df = 52$, $p = 0.0001$, 95% $C.I.$ $[-0.67, -0.26]$).

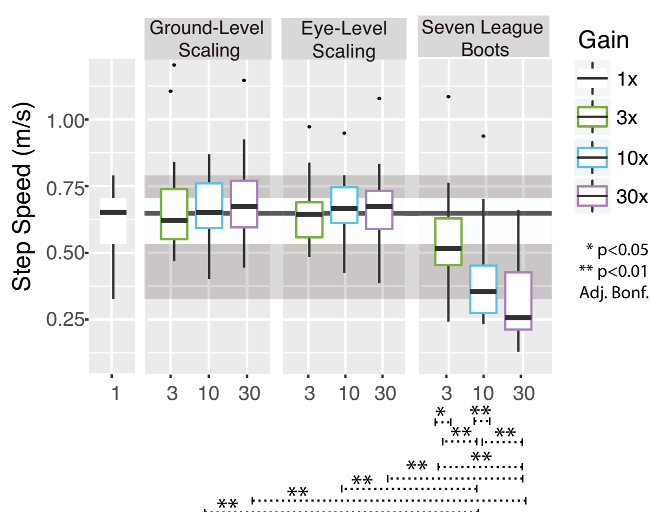

Figure 15: Average Step Velocity boxplots.

In the Ground-Level Scaling condition, participants who embodied the giant avatar walked faster (Pearson Correlation

(Step Speed x Embodiment) $cor = 0.53$, $t = 4.5$, $df = 52$, $p = 3.169e-05$, 95% $C.I.$ $[0.31, 0.70]$). Moreover, analysis with regards to demographics revealed that the average step velocity was significantly lower for non-gamers (Pearson Correlation: $cor = -0.21$, $p = 0.004$, $t = -2.89$, $df = 178$, 95% $C.I.$ $[-0.34, -0.067]$).

5 DISCUSSION

The user study results reveal that users significantly alter their walking behavior, including their stride length and walking speed, depending on the locomotion method used, the speed gain, and degree of embodiment. In the following section we discuss the strength and weaknesses of each technique and the types of scenarios they may be suitable for based on our findings.

Seven-League Boots

Seven-League Boots amplifies the users' movements along their walking path to create the illusion of longer steps.

Advantages. In this technique, the relative scale of the user's virtual representation and the virtual world is maintained. Moreover, when users are stationary, there are no apparent effects from the technique; therefore, users can observe and interact with the virtual world normally.

Disadvantages. When users are stationary, it is unclear whether the boots are active or not. Due to the lack of visual feedback, users only experience the speed gain after they have began walking. This technique may require training and time for acclimation, and may lead to greater instability, discomfort, and motion sickness at high gains (particularly with respect to Ground-Level Scaling). Positional accuracy also diminishes at high speed gains in Seven-League Boots.

Use Cases. The Seven-League Boots is suitable for VR applications that aim to closely replicate real experiences, while allowing users to walk with low speed gains ($\leq 3x$). This technique can also be used to create walking behavior changes in which users reduce their stride length and speed.

Ground-Level Scaling

Ground-Level Scaling increases users' avatar size relative to the virtual world, allowing them to walk farther.

Advantages. This technique provides users with an immediate visual feedback regarding the expected magnitude of speed gain. Ground-Level Scaling maintains positional accuracy and control even at high speed gains. It also results in greater sense of embodiment.

Disadvantages. Ground-Level Scaling requires wide empty virtual spaces that can facilitate scale changes. These changes of scale may break the illusion of reality. Moreover, due to the drastic vertical shift in eye level, users may miss the details of the virtual scene.

Use Cases. The Ground-Level Scaling technique can be used for Virtual Reality applications in which scale changes are appropriate and a strong sense of embodiment is desirable, including VR games and educational tools. This method is best suited when exploring large virtual environments with wide empty spaces, such as a virtual city or a planetary scene. If the virtual scene is constrained, techniques such as XRay Vision [3] can be utilized to render occluded infrastructures. Ground-Level Scaling can also be used to create walking behavior changes in which users increase their stride length.

Eye-Level Scaling

Eye-Level Scaling enables users to walk through a World in Miniature while maintaining their eye level.

Advantages. In this technique users retain their eye level and can inspect the details of the virtual scene. Positional accuracy is also maintained, even at high speed gains.

Disadvantages. When using Eye-Level Scaling the sense of embodiment may be reduced and users will not be able to view their virtual avatar. Moreover, the placement of the miniature world relative to the user may obstruct the performance of interactive tasks. XRay Vision [3] can also be used in this scenario to enable users to view their avatar.

Use Cases. The Eye-Level Scaling technique is appropriate for Virtual Reality applications in which having an animated avatar or a strong sense of embodiment is not critical, such as third-person games. This method is best suited when exploring virtual environments with occlusions, such as a ceiling, without the need to perform interactive tasks.

Based on the strength and weaknesses of each technique, designers of Virtual Reality applications can select the suitable speed gain method to create their desired VR user experience and walking behavior.

6 LIMITATIONS & FUTURE WORK

Effects on Interactive Tasks

Our user evaluation was limited to a target following task: users walked towards a target, positioned themselves accurately on the target, and pulled the right-hand trigger. The techniques explored will impact how users perform other tasks in VR, including reaching, grasping, object manipulation, and obstacle avoidance. For example, we hypothesize that obstacle avoidance behavior will be significantly different when using the Ground-Level Scaling technique, as users might feel less compelled to navigate around obstacles. Future work should study the effects of these techniques at different speed gains on a broader range of interactive tasks.

Dynamic Speed Gain Changes

In this work, we have taken a binary approach to speed gain in which the locomotion method is either on or off. The speed gain can change instantaneously or gradually, during movement or when the user is stationary. Dynamic control-to-display gain based on mouse velocity is a common technique used on desktop graphical user-interfaces. Exploring similar techniques for speed gain in VR is an interesting direction for future work. However, this topic should be approached with caution, as dynamic speed gain changes might have negative consequences. Research on Seven-League Boots has suggested that gradual increases or decreases in speed may induce a sensation of lag in the tracking system [14]. Moreover, prior work on multi-scale traveling has found scale changes during movement to be ineffective [36]. In our preliminary explorations we found that users may feel simulation sickness as a result of dynamic changes in scale. However, similar to redirected walking techniques, gradual and slight gain changes may be possible without inducing motion sickness or a sensation of lag.

Interaction Techniques

During our user evaluation, the locomotion techniques were activated automatically by the experimenter. In some VR applications it is necessary for the user to be in control of activating/deactivating the method and setting the speed gain. Future work should explore various interaction techniques that may be appropriate for each technique. These include:

Controller-Based. Hand-held controllers can be used to activate/deactivate the methods and to modify the speed gain. However, this could be detrimental to the experience, as one of the advantages of physical walking over other locomotion techniques such as teleportation, is that it does not require additional hardware.

Walking Speed. Similar to Superhuman Jumps, the speed gain methods can be activated when users reach a pre-specified peak acceleration during movement, and deactivated when they stop walking.

Gestures. Full-body gestures, such as reaching up, similar to the Ninteno Labo Robot Kit [24], can be used to activate the Ground-Level Scaling method. Two-handed zoom gestures, similar to those used in the MakeVR CAD tool [15], can also be used to initiate scaling and to specify its magnitude.

Limited Physical Space

The techniques that we explored allow users to travel much farther in the virtual world compared to the real world. However, these do not fully address the problem of limited physical spaces and users will eventually reach the boundaries of their physical environment. In such scenarios, the suggested methods need to be combined with other locomotion techniques, such as redirected walking or warped spaces. Redirected walking manipulates users' rotational movements and imposes unnoticeable changes in the direction of the users' path [26]. Warped spaces fold large virtual scenes into smaller physical spaces by altering the rendering [30]. Future work should study the interactions between these techniques and the explored methods (Ground-Level Scaling, Eye-Level Scaling, and Seven-League Boots). For example, it is important to understand how scale changes affect sensitivity to rotational gains in redirected walking [28].

7 CONCLUSION

We explored three methods for increasing users' effective travel speed in VR: (1) *Ground-Level Scaling* increases users' avatar size, allowing them to walk farther in the virtual world. (2) *Eye-Level Scaling* enables users to walk through a World in Miniature, while maintaining their eye level. (3) *Seven-League Boots* creates the illusion that every step is longer in the virtual world, by amplifying users' movement along their walking path. We conducted a study comparing these methods and found that Seven-League Boots is less preferred by users and positional accuracy diminishes at high speed gains using this method. Moreover, users significantly alter their walking behavior depending on the method used, the speed gain, and how much they feel embodied. At high gains users took larger steps in the Ground-Level Scaling condition and smaller steps in the Seven-League Boots. Users also slowed down at high gains using the Seven-League Boots.

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