Walking Telescope: Exploring the Zooming Effect in Expanding Detection Threshold Range for Translation Gain

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Abstract. Redirected Walking (RDW) is a locomotion technique utilized in virtual reality. It involves manipulating the displayed scene to redirect the user without their awareness, causing them to adjust their position and orientation naturally in response to perceived motion. This technique enhances the user's immersion and smoothens their exploration of the virtual environment, enabling them to navigate a greater range of virtual spaces within a confined physical area. One key element in redirected walking is translation gain, which scales the speed of the user's virtual movement, allowing them to traverse the virtual environment faster or slower. However, its effectiveness is constrained by the detection threshold imposed on it. Since translation gain primarily capitalizes on the imprecision of human distance perception, while in real life telescopes can also confuse people's judgment of distance, taking inspiration from this phenomenon, we propose an approach called Walking Telescope. The Walking Telescope approach involves modifying the field of view (FoV) by filling the entire headset view with a small range of viewpoints. We discovered that the threshold range of translation gain expands when the FoV is smaller than the original FoV of the headset. Furthermore, as the FoV gradually decreases, the threshold range of translation gain progressively expands. As a comparison, we also experimented with reducing the FoV by simply decreasing the visual range. This method does not produce a zoom-in effect similar to that of a telescope. To ensure user comfort, we identified a suitable FoV range by calculating the Simulator Sickness Questionnaire (SSQ) score. This approach allows for an expanded threshold range for translation gain without reducing the user's comfort level.

Keywords: Virtual reality · Redirected walking · Translation gain · Field of view · Zooming effect · Perspective distortion

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1 Introduction

It is essential for virtual reality(VR) tasks to achieve high fidelity and unrestricted movement in a virtual environment. However, due to physical space limitations and the presence of obstacles, it is impossible to create a one-to-one mapping between a user's movement in physical space and their movement in virtual space. Various techniques have been developed to enable users to explore virtual spaces more freely within the limitations of physical environments. These techniques include Walking-in-Place [8,26,37], Omnidirectional Treadmills [5], and Redirected Walking [30,32] techniques. Among these techniques, RDW provides users with a more intuitive and natural walking sensation. It has been proven to improve the sense of presence and allows users to accurately perceive proprioceptive, kinesthetic, and vestibular stimulation [27]. After conducting research and implementing RDW techniques in recent years, it can be categorized into two types based on the objects being manipulated: perceptual manipulation and virtual space manipulation. Among them, perceptual manipulation involves adjusting the user's visual perception of the virtual view, while virtual space manipulation involves manipulating the structure of the virtual space [6]. Our research focuses on the field of perceptual manipulation.

RDW methods based on perceptual manipulation typically involve subtle modifications to the motion mapping between physical space and virtual space. This causes the user to follow a virtual path that deviates from their physical walking path, although the user remains unaware of the subtle difference. To achieve this subtle perceptual manipulation, traditional RDW technology introduces several redirection techniques, including translation gain, rotation gain, and curvature gain. The translation gain and rotation gain scale the speed of translation and rotation, respectively, for the user when moving in the virtual space. The curvature gain modifies the virtual heading direction when the user is walking forward. Many studies have explored the factors that can affect the threshold range of these gains, such as the FoV [38], the user's movement speed [41,25], the visual density of the virtual environment [29] and etc. In subsequent studies, other factors related to perceptual manipulation, such as bending gain and vertical gain (for jumping movements) gradually emerged. These studies have enhanced the implementation methods of redirection gain and have brought about more possibilities for RDW technology.

Our research focuses on translation gain, which is used to adjust the user's movement speed in the virtual environment. This adjustment allows the user to walk faster or slower in the virtual environment compared to the real world. We wanted to investigate whether there are any unexplored visual factors that can expand the threshold range of translation gain. Since the translation gain primarily capitalizes on the inherent uncertainty in human perception of distance, and the use of a telescope can further complicate the user's ability to judge distance accurately, we considered employing a telescope-like effect to expand the threshold range of the translation gain. We call this method the Walking Telescope. Since the Walking Telescope essentially modifies the FoV, we first examined the impact of adjusting the FoV through the Walking Telescope method. We also compared this with directly reducing the visual range of translation gain to assess the effects. To evaluate the effectiveness of this method, we employed a two-alternative forced choice (2-AFC) task [22] to collect users' perceptual data, which was subsequently used for the final psychological curve fitting. Analyzing the data revealed that altering the FoV by directly decreasing the visual range had no notable effect on the threshold range of translation gain. Conversely, employing the Walking Telescope approach had a substantial impact on translation gain. Having established that the Walking Telescope significantly affects translation gain, we sought to determine a more user-friendly modification scale. To achieve this, we utilized the SSQ score [11] to evaluate user comfort before and after each set of experiments.

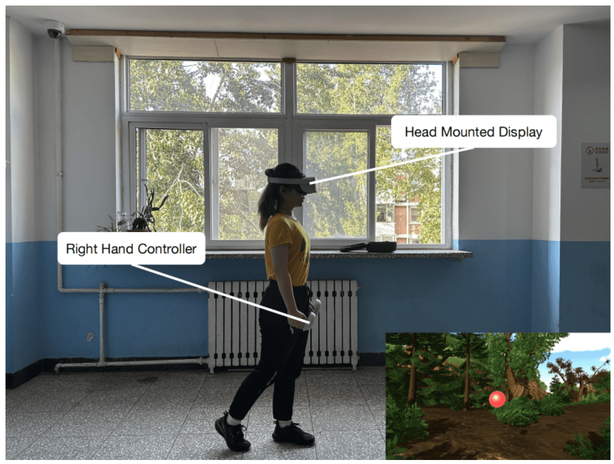


Fig. 1: Illustration of the experimental setup: a user is walking forward in the physical space, towards the direction of the red ball in the virtual space. Translation gains are applied in the experiment to modify the speed at which users move in virtual space. The inset shows the user's view of the virtual space, where a red ball is displayed.

Overall, our study has the following contributions:

1. We have developed a novel method of altering the FoV on headsets. This method involves filling a small area of the scene into the full view of the headset. As this technique simulates the experience of walking with a telescope, we have named it the ”Walking Telescope”.
2. Through experiments, we found that changing the FoV affects the user's perception and confuses their perception of speed and distance, thereby expanding the threshold range of translation gain.
3. At the same time, we also found that as the FoV decreases further (modified by Walking Telescope), the user's perception of translation gain becomes less and less sensitive, that is, as the FoV decreases, the threshold range of translation gain increases.

2 Related Work

The paper's investigation builds upon advances made in several related works, including the detection threshold for translation gain, the impact of FoV changes and magnified view on distance perception. These areas of research are crucial for understanding and enhancing the concepts of RDW and translation gain in relation to FoV change.

2.1 Translation gain detection threshold

RDW techniques can be classified into two main categories: subtle and overt manipulation [17]. Subtle manipulation involves making imperceptible alterations to the virtual environment to create the illusion of larger virtual spaces, while overt manipulation involves more noticeable changes. Although overt manipulation can provide benefits in situations where there is very limited physical space, it can also lead to increased discomfort if users become aware of the manipulations. To optimize the sense of presence and enhance the overall user experience, subtle manipulation is generally the preferred approach.

Within the realm of subtle manipulation, it is important to determine the appropriate range for translation gain, which refers to the extent of virtual movement for a given physical movement. This study [32] has suggested that the range of translation gains in the virtual world should be limited to 0.86 to 1.26. This ensures that users do not notice significant changes in their walking speed.

Another study [39] investigated the detection threshold of translation gains in 360° video-based telepresence systems. In this setup, users wear VR headsets that provide a view of the real world. This study identified a threshold range of 0.942 to 1.097 for translation gains. These findings show that the detection threshold range is smaller compared to experiments conducted solely in the virtual world. It can be inferred that the level of realism in the environment and the sense of immersion for the player affect the detection threshold range of translation gain. With increasing levels of environmental realism and player immersion, the detection threshold range of translation gain may correspondingly increase.

The inference can be further supported by the results of a study [15] that investigated the impact of visible virtual feet on users' perception of translation gains. In a high-fidelity visually rich virtual environment (VE), this study observed a range of 0.85823 to 1.26054 for translation gains when virtual feet were not visible, and a range of 0.87583 to 1.15388 when virtual feet were visible. Importantly, in a low cue VE with visible virtual feet, the observed range was 0.72745 to 1.25038. These findings suggest that participants were generally better able to estimate their walking velocity in visually rich environments compared to environments with reduced cues. Furthermore, the presence scores were lower in the reduced-cue environment compared to the visually rich environment without virtual feet. These results have highlighted the significance of the virtual environment in influencing visual perception compared to self-representation. However, if it were experimented with more complex visual self-representations, such as avatars, it may yield different results.

Simultaneously, two papers [34,36] primarily focus on aligning the physical environment (PE) with the virtual environment (VE) by overlapping virtual and real obstacles. This approach aims to expand the walkable space in the physical environment rather than compressing it due to obstacles within the VE. This incorporation holds merit, as establishing a robust mapping between VE and PE has the potential to facilitate tactile interactions, thereby enhancing the sense of presence. This, in turn, could lead to improved manipulation of gain thresholds in Redirected Walking. Interestingly, this mode of operation might not diminish the gain threshold with an enhanced sense of presence. This is because the induced sense of presence has an influential, rather than diminishing, effect.

Moreover, a study [12] demonstrated the impact of room size, object presence, and spatial layout on the threshold range of Relative Translation Gain (RTG). In layouts such as Scattered and Peripheral, objects frequently enter and exit the user's field of view while walking, consistently diverting their attention from their walking speed. The centered layout, however, allows users to accurately perceive and predict their location, regardless of their position or direction along the walking path. This layout allows users to maintain a fixed presence of objects in their sight, helping them estimate their walking speed based on their perceived proximity or distance from these objects. Additionally, a study with similar findings [13] suggests that relative translation gain thresholds tend to be higher in larger spaces.

In another study [40], it was observed that a gradual change in translation gain can result in a wider range of threshold gains without being perceptible. Furthermore, prior research in the study [3] found that users frequently underestimate their walking speed in the VE, which implies a higher potential value for the translation gain threshold.

In summary, these findings from related studies emphasize the importance of considering multiple factors, such as the VE, room size, presence of objects, and spatial layout, when examining the threshold range of relative translation gain and its impact on users' perception of walking speed in virtual environments. A realistic representation of both the VE and self-presentation can narrow the threshold range of translation gain without the user's awareness, unless such narrowing is intentional and effectively executed for misdirection purposes. Hence, meticulous control over all variables is imperative to prevent any extraneous factors from influencing the measurement of how a specific variable affects the threshold for translation gain.

2.2 Impact of FoV change on distance perception

The impact of FoV changes on users' distance perception is a topic of ongoing research. A past study [14] has suggested that varying FoV is not directly the cause of distance underestimation problems. Another study [21] states that the reduction of FoV is more related to a decrease in the precision of distance perception rather than distance underestimation. More studies have also shown that FoV size can affect perceived heading and distance perception in virtual environments [24]. Manipulations of FoV within and across newer head-mounted displays (HMDs) suggest that FoV is an important factor for distance perception in virtual environments [4].

In a more recent study [23], the effects of FoV were specifically examined by manipulating the horizontal field of view (HFoV) and vertical field of view (VFoV) within an egocentric virtual environment using software. Their action-based assessment revealed that VFoV did not significantly influence distance perception, whereas HFoV had a noticeable effect on distance judgments. Notably, wider HFoVs resulted in more accurate assessments of distance.

Another perspective can be drawn from a previous study [19] which reported a decrease in the sense of presence with lower FoV. Considering the relationship between a lower sense of presence and a larger range of subtle gain thresholds observed in the aforementioned studies, it can be suggested that reducing the FoV directly affects the range of gain thresholds. This assertion is further supported by the work [38] that investigated the impact of FoV on participants' perception of rotational gain. Their findings indicated that participants exhibited a wider range of rotational gain thresholds with a lower FoV. However, this study did not explore the impact of FoV on translation gain.

2.3 Impact of magnified view on distance perception

From the aspect of magnification produced by a stationary low-vision telescope, it can result in a compression of perceived depth [31]. The compression of perceived depth is influenced by various factors, such as monocular viewing and a restricted field of view [31,28]. A severely restricted field of view can result in a substantially greater compression of perceived depth [28].

Based on these studies, it is evident that changes in field of view (FoV) and magnified view have a similar impact on distance perception, affecting the detection thresholds of translation gain. This may be because the visual transformations caused by both factors are similar. Magnified view also reduces FoV, but it achieves this by first reducing the FoV and then expanding the visible interface of the current FoV to fill the entire view of the HMD. The implications of FoV changes and a magnified view on increasing the range of gain detection thresholds are complex and require further investigation.

In summary, extensive research has been conducted to estimate the detection thresholds for RDW techniques. Additionally, studies have focused on determining the rotation gain thresholds for RDW, taking into account the FoV and investigating the impact of FoV changes on distance perception in VR. However, to the best of our knowledge, our work stands out as the first of its kind to investigate the impact of manipulating FoV through a magnifying view and translation gain in combination with users' walking behavior. Our goal is to identify the precise translation gain values that users are unable to detect under these unique conditions.

3 Method

3.1 Translation gain

Moving in physical space, we can usually perceive our state of movement more accurately through various sensory cues, such as vestibular perception, proprioception, and visual information. In immersive virtual environments (IVE), an accurate sense of motion is typically provided by a HMD with a tracking system. In order to enable the user to walk naturally in IVE while improving the naturalness of the VR interaction task, an obvious approach is to transfer the tracked user's head movements to the changes of the camera in the virtual world through one-to-one mapping. The disadvantage of this technique is that the user's movement is constrained by the limited range of the tracking sensor on the HMD and the relatively small workspace in the physical space. Therefore, it is almost impossible to directly achieve omnidirectional and unrestricted walking.

It is known from perceptual psychology that vision tends to dominate when proprioception and vestibular sensation do not coincide [33,1]. In the perception experiment, human participants could only rely on vision to assess their motion through the virtual scene. They were able to accurately determine the immediate direction of their movement, but struggled to perceive their path of travel [35,10]. Therefore, people started exploring how to guide users to follow a specific path in reality, which may differ from the path users perceive in virtual space. One aspect of exploring this topic was to investigate the extent to which the user's walking path in physical space could be scaled. The factor used for scaling is called the translation gain. It is calculated as shown in Equation 1.

$$g_t = \frac{T_{virtual}}{T_{physical}} \tag{1}$$

Where $T_{virtual}$ represents the distance traveled by the user in the virtual space and $T_{physical}$ represents the distance traveled by the user in the physical space. The computation of T can be expressed as shown in Equation 2.

$$T = P_{current} - P_{previous} \tag{2}$$

In Equation 2, $P_{current}$ represents the current position of the user, and $P_{previous}$ represents the position of the user in the previous time frame.

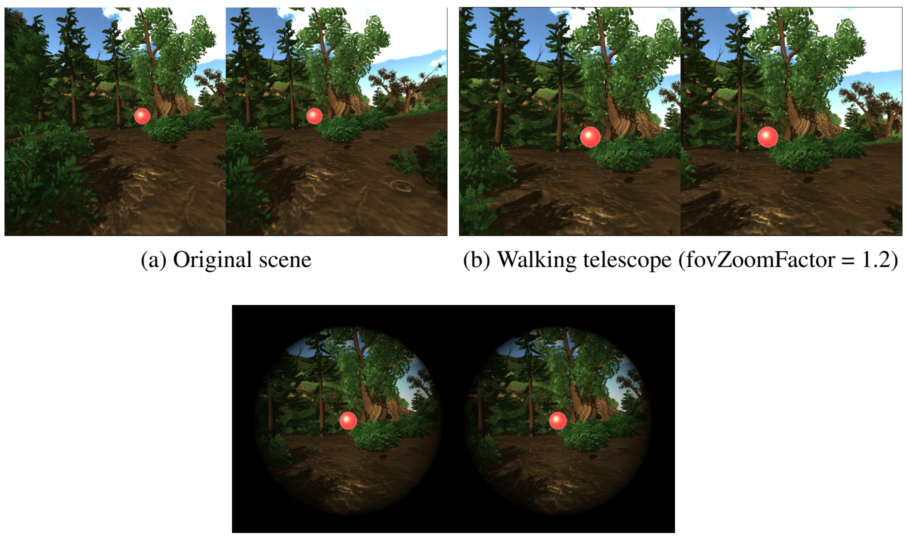
After applying translation gain, it is possible to subtly manipulate the user's translational motion in virtual space. Frank Steinicke et al. [32] explored the threshold range for human perception of translation gain, which is approximately between [0.86, 1.26]. When the translation gain is within this range, it is almost imperceptible to the user. Therefore most RDW algorithms apply a translation gain in this range. This paper is exploring how to expand the user's perceptual threshold range for translation gain by manipulating visual information.

3.2 Motivation

Translation gain mainly takes advantage of the user's uncertainty in distance perception, and the telescope will also affect the user's perception of distance. Inspired by this, we use the methods of filling the entire headset view with a small range of viewpoints to make the user feel like wearing a telescope after putting on the headset. This is obviously also a way to modify FoV, and we call this method the Walking Telescope. We used the factor XRDevice.fovZoomFactor to implement the new way of modifying the FoV. This factor will be described in Section 4.1.

In virtual reality applications, FoV refers more to what is visible when wearing a HMD. Most HMDs have a limited FoV, ranging from 40° to 110° [2], which is much smaller than the human FoV. In virtual reality, the most common technique to limit the user's virtual FoV is called "Vignette", which gradually reduces the user's FoV by reducing the brightness or saturation of the virtual camera from the center towards the periphery. This is generally achieved by applying black or some blurring effect to the peripheral field of view.

Based on research by Jonathan E. Hopper [9], we learned that using Vignette to limit the FoV will affect the user's perception of forward movement speed, and human perception of speed is related to the perception of distance. Based on the above description, we designed a set of verification experiments before the formal experiment to explore whether the two methods of modifying FoV, Vignette and Walking Telescope, would have an impact on the threshold range of Translation gain. Among them, the parameter fovZoomFactor used to adjust the Walking Telescope is set to 1.2. The binocular image of experimental scenario seen by the user is shown in Figure 2.



(a) Original scene (b) Walking telescope (fovZoomFactor = 1.2)

(c) Vignette

Fig. 2: Experimental Scenarios from the user's binocular perspective. **(a)** shows the original scene. **(b)** shows the scene after modifying the FoV with the Walking Telescope. **(c)** shows the scene after modifying the FoV with the Vignette.

3.3 Verification experiment

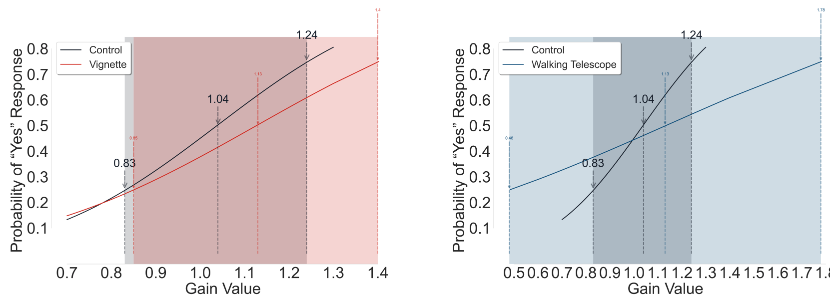
Procedure There were eight participants in this experiment, including five males and three females, whose average age was at 23.5 years. The device used for this experiment was the Oculus Quest 2, which is identical to the device used for the main experiment. The specific parameters of the HMD will be described in Section 4.2. Illustration of the experimental setup was shown in Figure 1.

Each user was required to complete a 3 (Type: Control, Vignette, Walking telescope) × 7 (Gains: 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3) × 6 (Blocks) scale experiment. In the virtual forest scene, the user will see a red ball, and the user needs to walk towards the ball, and in the process, carefully experience how their walking speed differs from that in the real space. After reaching the ball, the user needs to complete 2-AFC tasks. At this time, the user will see a blue canvas with the question, ”Do you think you move faster in virtual space than in physical space?” There will be two options (Yes, No) below the question. After the user completes the selection, he/she needs to turn around and continue walking towards the ball. Repeat the above process until the experiment of a ”type” is completed. If users feel uncomfortable, they can take a break and rest for a while. The data collected during the experiment will be fitted with psychometric functions to compare whether there have been significant changes in the lower detection threshold (LDT) and upper detection threshold (UDT) before and after changing the FoV.

Result The curves of the data from the verification experiment after fitting the psychometric function are shown in Figure 3. (a) is the comparison of the threshold ranges between the Control group and the Vignette group, and (b) is the comparison between the Control group and the Walking Telescope group. The black curves in both figures represent the fitting results of the Control group, while the black translucent area indicates the threshold range of the Control group. The red curve in (a) represents the fitting result of the Vignette group, and the red translucent area represents the threshold range of the translation gain after using the Vignette to change the FoV. The blue curve in (b) represents the fitting result of the Walking Telescope group, and the blue translucent area represents the threshold range of the translation gain after using the Walking Telescope to change the FoV. For specific data, please refer to Table 1. The threshold range of the control group is [0.83, 1.24], and the point of subjective equality (PSE) is 1.04. The range of the Vignette group is [0.85,1.40], and the PSE is 1.13. The range of the Walking Telescope group is [0.48, 1.78], and the PSE is 1.13.

It can be intuitively seen from the image that both methods of changing the FoV have an effect on expanding the threshold range of the translation gain. But we can also find that the effect of the Vignette is not obvious, while the effect of the Walking Telescope is very significant. So, we hope to further explore the effects of the Walking Telescope. However, during the verification experiment, users communicated their experience of using the Walking Telescope, we discovered that changing the FoV with the Walking Telescope can induce dizziness in users. So, we also need to consider whether the Walking Telescope has an impact on user comfort.

It is evident that our verification experiment was not rigorously designed. In this process, our experimental samples were insufficient, we did not perform statistical analysis on the user's experience, and we did not control the user's rest time. This operation will generate numerous interference factors, which are not conducive to data analysis. Therefore, in the main experiment, we expanded the number of experimental samples and refined the details to further explore the role of the Walking Telescope and ensure the rigor of the data.



(a) Control vs Vignette (b) Control vs Walking Telescope

Fig. 3: The curve of the data from the verification experiment after fitting the psychometric function. (a) is a comparison of the results between the Control group and the Vignette group, and (b) is a comparison between the Control group and the Walking Telescope group. The black curves in both figures represent the fitting results of the Control group, while the black translucent area indicates the threshold range of the Control group. The red curve in (a) represents the fitting result of the Vignette group, while the red translucent area represents the threshold range of the translation gain after applying the Vignette to modify the FoV. The blue curve in (b) represents the fitting result of the Walking Telescope group, and the blue translucent area represents the range of the translation gain threshold after using the Walking Telescope to change the FoV.

4 Main experiment

4.1 Design and Hypotheses

We define the purpose of the main experiment as exploring the impact of the Walking Telescope, a method of changing FoV, on translation gain.

Since we are using Unity to develop this experiment, we cannot directly modify the FoV of the camera to achieve the effect of a Walking Telescope after connecting to the HMD. Instead, we utilize XRDevice.fovZoomFactor, a factor provided by Unity, to modify the FoV of the HMD. The fovZoomFactor works as follows: suppose the default FoV of the headset is 100 degrees, and when the fovZoomFactor is set to 2, the FoV of the headset will be changed to 100/2 = 50 degrees. Since the fovZoomFactor of 1.2 in the validation experiment already induced a strong sense of vertigo in the user, we will use ”1.07, 1.14, 1.2” (small, smaller, smallest) as the test values for fovZoomFactor, while ”1” will be used as the control value for the test. The HMD we used was the Oculus Quest 2, which has an approximate FoV of 100 degrees. Therefore, the terms control, small, smaller, and smallest correspond to FoV angles of approximately 100 degrees, 93 degrees, 88 degrees, and 83 degrees, respectively.

Gain values were taken at 0.1 intervals in the region [0.6, 1.4], for a total of 9 values. In order to minimize the impact of the order in which the gain values appear in the experiment, we utilized a Latin square design to balance the sequence of the

Table 1: Verification Experiment Results. Among them, the first column shows the method for changing the FoV. LDT and UDT represent the lower detection threshold and upper detection threshold of translation gain, respectively. PSE represents the point of subjective equality.

Type	LDT(25%)	PSE	UDT(75%)
Control	0.83	1.04	1.24
Vignette	0.85	1.13	1.40
Walking Telescope	0.48	1.13	1.78

experiments. This required 9 blocks to complete the test, ensuring that each of the 9 gain values appeared only once in each block.

We asked each user to perform a 4 (Type: control, small, smaller, smallest) × 9 (Gains: 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4) × 9 (Blocks) scale experiment to evaluate the effect of the FoV on translation gain.

In the experiment, we deployed a 2-AFC task. The 2-AFC task avoids subject response bias because participants must make a judgment between two choices, even if they are unsure of the perceptual outcome. Typically, when users do not know the answer, they randomize their choice, giving themselves a 50% probability of being correct.

After the user puts on the HMD, they will appear in a clearing place of a forest scene, and a red ball will appear 5 meters in front of them. The user's task is to walk towards the ball and feel how their movement speed is different from normal. When the user is close enough to the ball, the ball and the scene disappear, and a question is asked, "Do you think you move faster in virtual space than in physical space?" (Yes, No). At this point the user can use the right hand controller to make a selection, the controller will emit a blue ray. When the ray hits the option, press the "A" button of the controller to select. If the user experiences a significant increase in speed, they should select the "Yes" option. If they do not feel any difference or if they are moving slower than usual, they should select "No". After selecting the option, the scene will reappear and the user will see the prompt "Please turn around to find the red ball", and the user needs to turn around, find the ball and start the next walk. After selecting "Yes" or "No" 9 times, a green canvas will appear, signaling the end of a block. This green canvas can prevent users from becoming perfunctory in completing 2-AFC choices as the task is too repetitive and boring, which will lead to inaccurate results in the statistics. Repeat the above steps until a purple canvas appears. At this point, one complete set of the experiment is finished, and the user must take a 10-minute break before starting the next set of experiments. The flow of the experiment and the scene seen by users during this process are shown in Figure 4.

The hypothesis of this experiment is:

- [H1] The size of FoV will have an effect on the threshold range of translation gain.
- [H2] The smaller the FoV, the larger the threshold range for translation gain.

- [H3] Changing the FoV using the Walking Telescope will not cause discomfort to the user.

During the experiment, each user was required to do 4 sets of experiments with different FoVs on the same day, and the user was forced to rest for 10 minutes between each set of experiments. In addition, each set consist of 9 blocks of test, and the 9 gain values will appear and only appear once in each block. The experiment took a total of 7 days to complete.

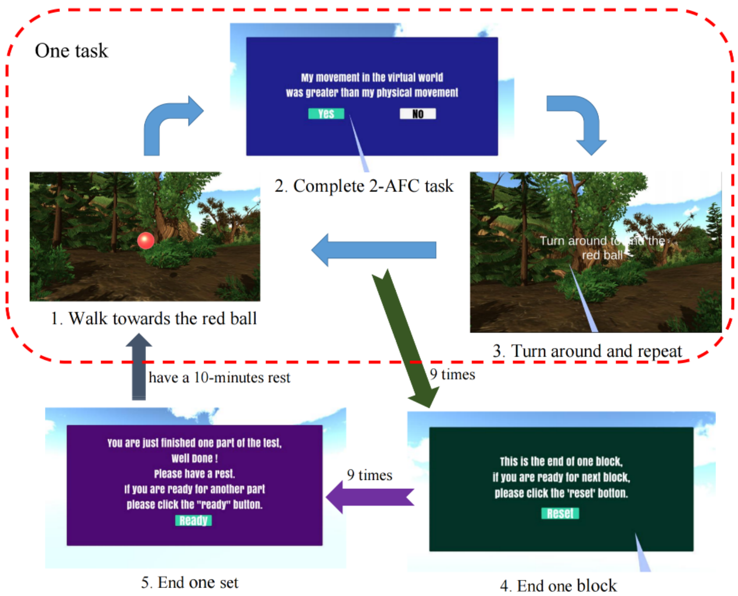


Fig. 4: First-person perspective experimental flow chart. At the beginning, a red ball will appear in front of the user, the user needs to walk towards the ball. When the user reaches the position where the ball is located, all scenes will disappear and a 2-AFC task will appear. After the user selects, the scene reappears and the user can see the prompt "Turn around to find the red ball". At this point, the user turns around and continues towards the red ball, repeating the process. Every time a block is completed, a prompt will appear to prevent users from becoming perfunctory in completing 2-AFC choices, as the task can be repetitive and boring. After completing all blocks for a group, a prompt will appear, forcing the user to rest for at least 10 minutes.

In order to get the user's comfort level, we used the SSQ questionnaire, and at the end of the bootstrapping process we ask the user to complete the pre-SSQ questionnaire to get an initial score. At the end of each test set, the user will be asked to complete another post-SSQ questionnaire. Finally, we will evaluate the user's comfort level at different FoVs based on the scores from the two questionnaires.

4.2 Apparatus

We used Unity3D 2021.3.21f1c2 64-bit (with the Oculus Integration plugin) for the development of experimental tasks. The participants used an Oculus Quest 2 HMD with a monocular resolution of 1832*1920, a refresh rate of 90Hz, and a FoV of approximately 100 degrees. Before the test, we calibrated the pupil distance of the HMD for each participant (the Oculus Quest 2 has 3 stops) to avoid blurring the scene and affecting the effect. Since all participants were right-handed, the right hand controller was used for selection. At the same time, since our experiments required the user to roam around the scene, air link was used to connect the device in order to prevent the user from tripping over by wires and to allow the user to walk around the space more comfortably.

4.3 Participants

In order to make the experiment more confident, we used more participants than when we conducted the verification experiment. The experiment consisted of 20 users, 9 females and 11 males, with an age distribution between 22 and 30. All of the participants were graduate students at the Beijing Information Science and Technology University. Only two of the participants had normal vision and did not wear glasses, while the rest had varying degrees of myopia. However, all participants wore glasses during the experiment and were able to clearly see the experimental scene. Before conducting the experiment, we also assessed the participants' prior experience with VR. Out of the twenty participants, eight had previous experience with VR, while the remaining twelve had no prior exposure to VR.

4.4 Procedure

Before conducting the formal experiment, we requested the participants to complete basic information questionnaires. These questionnaires included inquiries about the participants' age, gender, and prior experience with VR. Then, we explained and guided the participants through the experimental tasks, assisted them in wearing and adjusting the headset, and then allowed them to complete a set of practice experiments to become familiar with the tasks. During this process, participants were given the opportunity to ask questions in order to avoid any instances of misunderstanding the experimental process and the tasks they were required to complete. Of course, we don't answer questions like ”What is the value of the currently applied gain?”. The data obtained from the experimental tests will not be included in the formal data analysis. After the completion of the bootstrapping process, participants were instructed to fill out the pre-SSQ questionnaire, which was later used for comparison with the post-test vertigo assessment.

For each formal experiment, participants are instructed to navigate the virtual environment using the HMD and perform 2-AFC tasks. After the completion of each set of experiments, it is mandatory for the user to take a 10-minute break before proceeding to the next set of experiments. After each set of experiments, participants were instructed to fill out the post-SSQ questionnaire in order to evaluate the level of comfort experienced in each FoV. Each set of tests required approximately 15 minutes of the participant's time, resulting in a total duration of 90-100 minutes for each individual to complete all the experiments.

5 Results

5.1 Direction thresholds

We recorded the choice of every participant in each set of experiments. Then we used quickpsy (version 0.1.5.1)[20], an R Project, to perform the data analysis. The response of humans in a classification task with a binary response variable and a stimulus level as an explanatory variable is often binomially modelled as shown in Equation 3.

$$f(k;\theta) = \prod_{i=1}^{M} \binom{n_i}{k_i} \psi(x_i;\theta)^{k_i} (1-\psi(x_i;\theta))^{n_i-k_i} \tag{3}$$

Where f is the probability mass function of the model or the likelihood when considered as a function of the parameters. M represents the number of stimulus levels utilized in the classification task. x_i is the i-th stimulus level. n_i is the number of times that x_i is presented. $k = (k_1, k_2, ..., k_M)$is the vector of responses with k_i being the number of Yes-type (or correct) responses when x_i is presented. $\psi(x_i;\theta)$ is the probability of responding Yes when x_i is presented, it is called the psychometric function and has the form as Equation 4.

$$\psi(x;\theta) = \psi(x;\gamma,\lambda,\alpha,\beta) = \gamma + (1-\gamma-\lambda) * F(x;\alpha,\beta) \tag{4}$$

Where $\theta = (\gamma, \lambda, \alpha, \beta)$ is the parameter vector that defines the parametric family of probability mass functions for the model. γ is the guess rate and λ is the lapse rate, used to adjust the left and right asymptotes. α and β are the position and scale parameters. α controls the position of the psychometric function along the coordinates of the stimulus intensity, β controls the slope of the psychometric function. $F(x;\alpha,\beta)$ is a function with leftward asymptote 0 and rightward asymptote 1 - typically a cumulative probability function with a sigmoidal shape.

The psychometric function is used to simulate the subject's response to various levels of stimulation. The gain at which users answered "Yes" at a rate of 50% is referred to as the PSE, a value that represents the gain at which they are unable to perceive the stimulus. The detection threshold refers to the gain at which subjects have a 25% and 75% probability of selecting "Yes," while gain values between the two are considered imperceptible to the user.

The choice of F has little impact on the threshold computation, and we use the cumulative normal distribution function, as shown in Equation 5.

$$F(x;\alpha,\beta) = \frac{\beta}{\sqrt{\pi}} \int_{-\infty}^{x} exp(-\frac{\beta^2(x-\alpha)^2}{2}) \tag{5}$$

We calculated the gains corresponding to the 25%, 50% and 75% probability of a user choosing ”Yes”. Then, we use Analysis of Variance (ANOVA) [16] to analyze whether there is a significant effect of different FoVs on the threshold of translation gain.

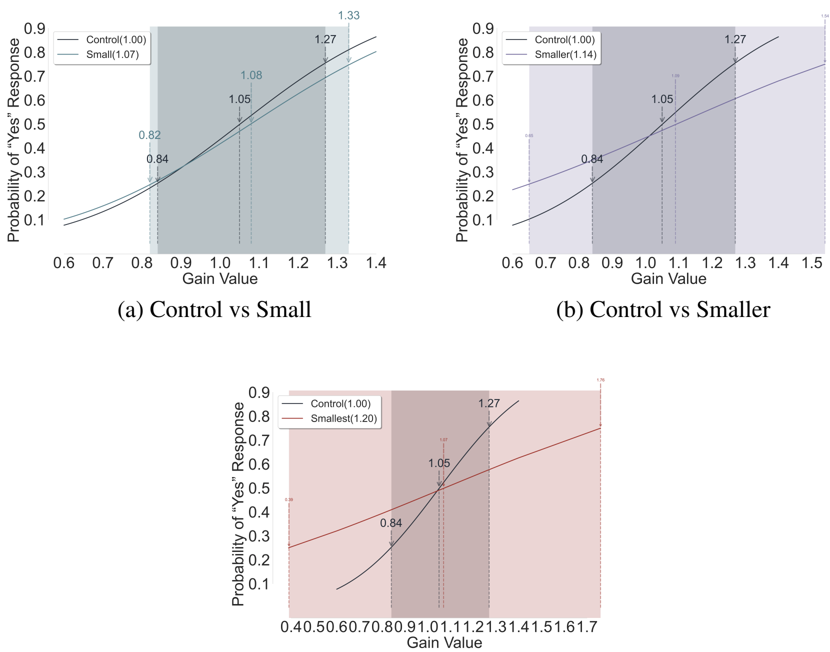
Table 2: Main experiment results. Among them, the first column represents the factor used to change the FoV. LDT and UDT represent the lower detection threshold and upper detection threshold of translation gain, respectively. PSE represents the point of subjective equality.

Type	LDT(25%)	PSE	UDT(75%)
Control(1)	0.84	1.05	1.27
Small(1.07)	0.82	1.08	1.33
Smaller(1.14)	0.65	1.09	1.53
Smallest(1.2)	0.38	1.07	1.75

The curves of the data from the main experiment after fitting the psychometric function are shown in Figure 5. (a) is a comparison of the results between the Control group and the Small group, (b) is a comparison of the Control group and the Smaller group, and (c) is a comparison of the Control group and the Smallest group. The black curves in all figures represent the fitting results of the Control group, and the black translucent area represents the threshold range of the Control group. The blue curve in (a) represents the fitting result of the Small group, while the blue translucent area represents the threshold range of the translation gain after applying the Small group's factor to adjust the FoV. The purple curve in (b) represents the fitting result of the Smaller group, and the purple translucent area represents the threshold range of the translation gain after applying the Smaller group's factor to adjust the FoV. The red curve in (c) represents the fitting result of the Smallest group, and the red translucent area represents the threshold range of the translation gain after applying the Smallest group's factor to adjust the FoV.

From the psychometric function fitting results we can see that the PSEs obtained from all four experimental groups including the control group were slightly greater than 1, which means that most of the subjects tended to overestimate their movement speed (refer to Table 2 for the exact values). The data in the table are briefly displayed and analyzed below. Combining Figure 5 and Table 2, we can see that the LDT of the curve fitted to the control group is 0.84 and the UDT is 1.27, which is roughly in line with the thresholds measured by Frank Steinicke et al. in 2009 [32], so we believe that the operation of this experiment is standardized and the data obtained have a high level of confidence.

We move on to the experimental group. In Section 4.1, we mentioned that the corresponding FoVs for the Small, Smaller and Smallest groups are approximately 93, 88 and 83 degrees, respectively. The threshold ranges obtained by the Small, Smaller and Smallest groups are [0.82, 1.33], [0.65, 1.53], and [0.38, 1.75], respectively.



(a) Control vs Small

(b) Control vs Smaller

(c) Control vs Smallest

Fig. 5: The curve of the data from the main experiment after fitting the psychometric function. (a) is a comparison of the results of the Control group and the Small group, (b) is a comparison of the Control group and the Smaller group, and (c) is a comparison of the Control group and the Smallest group. The black curves in all figures represent the fitting results of the Control group, and the black translucent area represents the threshold range of the Control group. The blue curve in (a) represents the fitting result of the Small group, while the blue translucent area represents the threshold range of the translation gain after applying the Small group's factor to adjust the FoV. The purple curve in (b) represents the fitting result of the Smaller group, and the purple translucent area represents the threshold range of the translation gain after using the Smaller group's factor to change the FoV. The red curve in (c) represents the fitting result of the Smallest group, and the red translucent area represents the threshold range of the translation gain after applying the Smallest group's factor to adjust the FoV.

It can be intuitively seen from the image that changing the FoV by using the Walking telescope will expand the threshold range of the translation gain. Analyzing the values from each group, it can be observed that the threshold range of the Small group is similar to that of the Control group. This suggests that making slight changes to the FoV of the HMD does not significantly impact the user's perception. However, a slight expansion of the threshold range can also be observed. Starting from the Smaller group, the change in the threshold range becomes obvious. The LDT of the translation gain extends from 0.86 to 0.65, and the UDT from 1.26 to 1.53. This indicates that the participant's speed can be altered to be 35% slower or 53% faster than the actual speed. And for the Smallest group, the LDT has been expanded from 0.86 to 0.38, and the UDT has been expanded from 1.26 to 1.75. This means that the participant's speed can vary from being 62% slower to 75% faster than the actual speed. From the above data, it can be seen that none of the expansions of the LDT are as large as the expansion of the UDT, but they are still quite impressive. To ensure the accuracy of the data, we utilized the aov function in the R project to perform a variance analysis on the variable Type. We found a significant main effect of Type $(F(3, 76) = 6.859, p < 0.01)$ and Translation gain $(F(8, 171) = 28.952, p < 0.01)$. So, we can conclude that changing the FoV using the Walking Telescope significantly affects the translation gain. Additionally, we can confirm that the hypothesis [H1] is valid.

We can also analyze the data from an overall perspective. Looking at the threshold ranges of the three test groups - Small, Smaller, and Smallest together, we can observe a clear increase in the range span. The ranges from Small to Smallest are becoming larger and larger. Therefore, we can conclude that the threshold range of translation gain gradually expands as FoV decreases, and this supports the hypothesis [H2].

5.2 Simulator sickness

In order to measure the sense of vertigo of different FoVs, we counted the SSQ scores before and after the experiment, and from the data in table 3, the SSQ scores of the Control group were similar to the scores before the experiment, which were 12.47 and 13.09, respectively, indicating that the original FoV using the HMD was the most comfortable for the users. For the data of the experimental test group, the SSQ scores gradually increased from small to smallest, reaching 14.59, 16.64, and 29.21, respectively. From the individual data, the SSQ scores of the Small group were the closest to those of the Control group, and the difference with the pre-SSQ was 2.12. This indicates that making slight changes to the FoV of the HMD would not have a significant impact on the user's comfort. The value of Smaller group did not increase too dramatically, and the difference with pre-SSQ was 4.17, but in the process of the experiment, by asking the user's feeling, it was found that the FoV of Smaller group could make the user feel obvious vertigo. The difference between the SSQ score obtained by the Smallest group and the SSQ score obtained before the experiment has reached 16.74, indicating that it has caused significant discomfort to the users. It can be seen that using a Walking Telescope to modify the FoV to less than 85 degrees will cause obvious discomfort to the user, so the hypothesis [H3] cannot be proved.

In addition, we can clearly see that as the FoV decreases, the threshold range expands. However, this also leads to an increase in the discomfort experienced by the user.

Therefore, we recommend controlling the ”fovZoomFactor”, which is used to modify FoV within the range of [1.07, 1.14] in order to minimize user discomfort.

Table 3: SSQ-score. The first two columns represent the scores obtained from the SSQ questionnaires filled out by the users after completing the test group. The last two columns represent the name of the experimental group and the corresponding SSQ score, respectively.

Pre	Score	Type	Score
Test	12.47	Control	13.09
		Small	14.59
		Smaller	16.64
		Smallest	29.21

6 Discussion

In this paper, we first explored the effect of FoV on translation gain using two different methods. One method involved adding a Vignette, while the other involved filling the full headset view with a small range of viewpoints. We referred to the latter method as ”Walking Telescope”. In these experiments, we have demonstrated that the Vignette method does not have a significant impact on translation gain, whereas the Walking Telescope method does. Additionally, we have improved the experiments by conducting tests with various FoV sizes. As analyzed in section 5.1, the threshold range gradually expands as the FoV decreases.

Since the sensation of using a Walking Telescope is akin to walking with a telescope, we conducted an analysis to understand how a Walking Telescope impacts the threshold range of translation gain by examining the characteristics of walking with a telescope.

- Restricted field of view: Telescopes typically have a limited field of view, which restricts the user’s ability to see a wide area. This limited perspective can impact their perception of the surrounding environment, potentially affecting their walking speed.
- Visual Illusion: When wearing a telescope, the field of view is limited to a small area with a zooming effect, causing the surrounding scene to appear to move at a faster speed. This can create a false perception that we are walking at a faster speed, as the human brain estimates speed based on visual input.
- Wobbling: Wearing a telescope may introduce wobbling or shaking, which can make walking more difficult for the user as they need to adjust to additional visual distractions.
- Distraction: Wearing a telescope may divert the user’s attention from walking and cause them to focus more on observing distant objects. This can lead to inaccurate judgments of the user’s walking speed.

So, for these reasons, modifying our FoV will result in a more significant expansion of the threshold range for translation gain. However, in section 5.2, if the change in FoV is too significant, it will cause a sense of vertigo for the user. We analyzed this vertigo as resulting from a disturbance in the user's balancing system. Because the visual system and balance system play essential roles in coordinated walking, a Walking Telescope may disrupt the user's balance system, leading to a mismatch between the user's visual perception and the actual speed and direction of walking. As the magnification of the telescope increases, the sense of mismatch or confusion becomes more severe, along with the user's sense of vertigo as a result.

Overall, the telescope-like modification of FoV that we use allows for a wider range of thresholds for translation gain. However, it also has the drawback of making the user more prone to vertigo. Therefore, we recommend using the Walking Telescope only in specific scenarios, such as when there is a target in a VR task. In this case, utilizing the Walking Telescope can direct the user's attention. By focusing the user's attention on the target, the sensation of vertigo can be minimized.

7 Limitation and future work

By analyzing the data in section 5, we can conclude that the FoV has a significant effect on the translation gain. However, reducing the FoV may also decrease the user's comfort level, which is not ideal for users with motion sickness. Therefore, we conducted further research to explore potential solutions for alleviating vertigo caused by a smaller FoV.

Surprisingly, the Vignette we used in the previous validation experiments has been employed in certain virtual reality games to alleviate the user's vertigo [7]. From this, we hypothesized that adding a black border to the user's headset after modifying the FoV using the Walking Telescope could alleviate the user's sense of vertigo. However, due to time constraints, we have not been able to further validate this idea. We hope that interested researchers will collaborate with us in the future to further explore it.

Due to time constraints, we were only able to set up one scenario in our experiment, which was an outdoor forest scene. We have not been able to investigate whether the Walking Telescope has the same effect in indoor settings. Moreover, walking with a telescope indoors is not consistent with typical human behavior, so the Walking Telescope may not be suitable for VR tasks in indoor scenes.

In addition, it is evident that directly altering the user's FoV through the Walking Telescope will result in a diminished sense of presence. Furthermore, there is a question regarding the application of the findings obtained in our study. Therefore, we believe that we can continue to explore the idea of dynamically, smoothly, and gradually changing the user's FoV as they walk. In this way, by utilizing a larger translation gain, the user will not perceive noticeable alterations in FoV and will not experience vertigo. This idea could be explored in terms of how the translation gain and the FoV should be correlated. In other words, when applying gain to the user, to what extent can the FoV be adjusted to counterbalance the user's perception of the gain change? At what speed should the FoV change be difficult for users to detect? It is believed that incorporating these elements of inquiry will make our study more applicable in practical settings.

Looking ahead, we are also considering an integration with RDW techniques under the OpenRDW framework proposed by Miao Wang et al. [18]. This collaboration aims to explore whether combining our approach with OpenRDW techniques can further elevate the translation gain threshold, providing a more comprehensive understanding of the potential applications and advancements in Redirected Walking.

8 Conclusion

In this paper, we propose a method called Walking Telescope to change the FoV by expanding a small area of the scene to fill the entire view of the HMD. We also verified that the FoV size affects the user's perception of translation gain when walking. Our experimental results not only prove that FoV has a significant impact on the translation gain, but also demonstrate a specific pattern. Specifically, we found that as the FoV decreases, the threshold range extension increases. However, modifying the FoV using the Walking Telescope is not ideal for the user's experience and can cause varying degrees of vertigo. This is also a limitation of our exploration content. Therefore, we recommend setting the Walking Telescope parameter within the range of [1.07, 1.14] and utilizing it specifically in outdoor environments.

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