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•**Article**•

Redirected jumping in virtual scenes with alleys

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Abstract **Background** The redirected jumping (RDJ) technique is a new locomotion method that saves physical tracking area and enhances the body movement experience of users in virtual reality. In a previous study, the range of imperceptible manipulation gains in RDJ was discussed in an empty virtual environment (VE). **Methods** In this study, we conducted three tasks to investigate the influence of alley width on the detection threshold of jump redirection in a VE. **Results** The results demonstrated that the imperceptible distance gain range in RDJ was not associated with the width of the alleys. The imperceptible height and rotation gain ranges in RDJ are related to the width of the alleys. **Conclusions** We preliminarily summarized the relationship between the occlusion distance and manipulation range of the three gains in a complex environment. Simultaneously, the guiding principle for choosing three gains in RDJ according to the occlusion distance in a complex environment is provided.

Keywords Virtual reality; Virtual locomotion; Redirected walking; Redirected jumping; Detection threshold

1 Introduction

Scene exploration and scene navigation are crucial in virtual reality (VR); however, travel in a virtual space is always restricted by physical boundaries and obstacles. Therefore, many effective exercise techniques have been proposed, such as treadmill[1], walking in place[2], transmission[3], redirected walking (RDW)[4], and redirected jumping (RDJ)[5]. Moreover, RDW is more intuitive and natural, thus helping users to complete tasks. Many studies have been conducted on the RDW technique to detect thresholds of the rotation, translation, curvature, and bending gains[6]. The detection thresholds (DTs) are affected by the cave-like virtual environment (VE)[7] and 360° videos[8]. In addition, the field of view (FOV) affects these gains[9]. Compared with RDW[4], jump distance and rotation angle of the redirection jump have a wider manipulation range. In the same virtual space, the physical space required for the redirection jump is smaller. Therefore, RDJ needs to be further investigated to surmount the physical boundaries and obstacles for traveling in a virtual space.

Jumping is a fundamental human movement in the real world, such as jumping over gaps and obstacles. Recently, RDJ has been explored as a new locomotion technique in VR[5,10]. VEs have various occlusions, such as walls and objects. The occlusion distance is the distance between the occlusion and user. However, these DTs of RDJ[5,10] do not consider the occlusion distance. The influence of the occlusion distance on DTs requires further investigations. To study this effect in RDJ, we simplified the occlusion into alley scenes and changed the width of the alley to adjust the occlusion distance.

We estimated the DT of the distance, height, and rotation gains under different alley widths during RDJ. As such, we collected a two-alternative forced-choice (2-AFC) response from the subject, used these data to fit a two-dimensional (2D) psychometric function, and obtained the DT. Subsequently, we discussed and analyzed the range of DT in RDJ with an alley of various widths. Furthermore, we discussed the influence of occlusion distance on the DT of RDJ. To the best of our knowledge, this study is the first to investigate the influence of different virtual scenes on the DT in RDJ.

The remainder of this paper is structured as follows: Section 2 summarizes prior studies associated with the RDW, RDJ, and visual motion perception. Section 3 introduces RDJ, redirection gains, and jumping detection. Section 4 describes the user study design and discusses the results. Section 5 presents the limitations of our study and an overview of future work. Finally, Section 6 presents the conclusions.

2 Literature review

2.1 Redirected walking

Virtual scenes are often considerably larger than the physical space where a VR user can walk. Many studies have been conducted to explore natural walking of users in virtual scenes. Razzaque et al. proposed an RDW method, inspired by a blindfolded man, who was instructed to walk along a straight line, trying to manipulate the VE straight line; however, the subject unintentionally walked along an arc[5]. Steinicke et al. quantified the extent to which humans can redirect without observing inconsistencies between the real and virtual motions[11,12]. They reported that the rotation gain varied from 0.67 to 1.24, the distance gain varied from 0.6 to 1.4, and the curvature gain varied from −0.019 to 0.052. Langkehn et al. introduced a new redirection method based on bending gain, which defined the difference between the physical and virtual paths when both were bent[13]. They concluded that the DT of the bending gain was wider than that of straight walking. However, they did not consider the effects of other factors on the DT for RDW. In 2011, Neth et al. proposed that the speed at which a person walks affects the DT of the curvature gain of RDW[14]. They found that the sensitivity of walking on a curved path was significantly lower at lower walking speeds. Bruder et al. confirmed that cognitive tasks also affect walking behavior[15]. Williams et al. reported that an FOV of 110° has a wider range of DTs for rotation gain than an FOV of 40°[9]. Bölling et al.[16] reported that adaptation affects the perceptual thresholds and walking behavior. Reimer et al. found that the presence of a virtual body had no significant effect on the DT of translation and curvature gain[17]. In addition to these factors, some studies onsidered the effects of certain VEs on the DT. Sebastian investigated the possibility of a rotation gain in a cave-like VE[7]. They proposed that the rotation gain is in the range of [0.85∶1.18] in a cave environment. Zhang et al. investigated the ability of users to recognize the translation and rotation of RDW operations. They discussed that the translation and rotation gains in the 360° reality environment are different from those in VEs[8]. Therefore, the DT is affected by many factors in RDW. In addition, the VE also has a significant effect on the DT in RDW. However, the effect of VEs on the DT in RDJ, such as alleys, has not been sufficiently studied.

2.2 Redirected jumping

Jumping is a common action in the real world, such as jumping over a gap or an obstacle. Many researchers have investigated jumping in VR to simulate the actions of users by exploring scenes in the real world. In recent years, the focus of redirection studies has changed from horizontal to vertical. Matsumoto et al. found that the energy consumed during walking uphill is thrice that of walking on a flat ground, whereas the energy consumed by walking downhill is half that of walking on a flat ground[18]. On that basis, they achieved uphill and downhill motion by redirecting in the vertical direction. Matsumoto et al. reported that the range of vertical gain in the VE is wider than that in the fore−aft direction[19]. Simultaneously, they confirmed that the threshold range under drone conditions was wider, possibly owing to a narrower FOV.

The jumping process principally includes forward and vertical directions. RDJ was introduced to save the physical tracking area and enhance the body movement experience of users in VR[10]. Hayashi et al. developed the concept of RDJ and investigated the range of effective manipulation of three basic jumping movements: horizontal, vertical, and rotation. Subsequently, they discussed the range of imperceptible manipulation gains. In particular, the height during low jumps can be easily manipulated without the user noticing. Hayashi et al. presented a short VR experience, focusing on RDJ to reduce the physical tracking space[5]. They reported that the physical space could be reduced by 30% when using a gain factor of 2.0. Jung et al. examined the detection rate for different curvature gains in RDJ[20]. They found that designers could achieve greater manipulations in RDJ than in RDW. Additionally, they concluded that the potential combination of metaphors could further reduce the required physical space for locomotion in VR. This study focuses on the curvature gains to be compared with RDW. However, these studies did not consider the influence of the environment and other factors on the DT of RDJ. Consequently, different widths of the alleys led to different FOVs. Williams et al. showed that FOVs influence the DT of RDW. Our work focuses on investigating the effect of different alleys widths on the DT[9].

2.3 Visual motion perception

Scaling the movements of users in the VE affects the landmarks while altering the perceived speed of the optic-flow motion information. This manipulation of optic-flow cues might be a contributing factor in influencing self-motion perception[21]. An immersive VE significantly affects the user's perception of distance, spatial relationships in the VE, and perception of self-motion[22]. Steinicke et al. found that rotation, translation, and curvature could be under- or overestimated when users walk in VR[23]. Lappe et al. attributed this phenomenon to the perception of visual self-motion[24]. In VEs, different virtual scenarios and the field of vision of a user can also affect self-motion perception. Riecke et al. confirmed that simply presenting the scene upside down significantly affected the persuasiveness of the self-motion illusion[25]. Basting et al. proved that the FOV in a head-mounted display (HMD) influences the perceived vection of a user[26] . Riecke et al. reported that the effectiveness of motion simulations could be enhanced by using realistic visual stimuli[27]. These stimuli provide rich clues regarding image depth, relative distance, and visual orientation. Consequently, virtual scenes can affect self-motion perception. However, studies on the influence of various virtual scenes in RDJ on user self-perception are required.

3 Redirected jumping in alley scenes

This section explains the manipulation of distance, height, rotation, and jump state detection in RDJ.

3.1 Jumping detection

It is necessary to detect the jumping action of a user to investigate natural jumping behavior in VR. We bound Vive trackers (6-DoF) to the feet and waist of the user to obtain the position information of the feet and waist in real-time when jumping, and used the HTC Vive Pro helmet (2160×1200@90Hz, 110-degree diagonal field of view) to acquire the head position of the user. Figure 1 shows three Vive Trackers, two controllers, and an HMD on the body of a user.

We started recording the position of each frame in the real world after a user entered the jumping detection system. When the position of the current and first frames differed by more than 3cm, the system judged the user to be in a "jumping" state. The position difference between adjacent frames was considered as the change in the user position in the real world. The position change of the virtual camera in the VR world was correspondingly matched with the position of the user in the real world.

Figure 1 Experimental setup: An HMD, two controllers, and three trackers.

3.2 Redirection gains in redirected jumping

Jumping includes distance, height, and rotational movements. For these three movement directions, the distance, height, and rotation gains in RDJ have been presented[10]. These three gains define the mapping of real-world motion to that in the virtual world.

3.2.1 Distance gains in RDJ

When the user entered the jump detection system, we started recording the position of the user in the real world for every frame. The difference between the recorded position in the previous P_{pre} and current P_{cur} frames was the change in the position of the user detected by the system. The horizontal position change of the user in the real world is indicated by d_{real}. The position changes of the virtual camera $d_{virtual}$ in the VR world was correspondingly matched using the position of the user in the real world. The ratio between d_{real} and $d_{virtual}$ is considered as the distance gain: $d_{virtual} = d_{virtual}/d_{real}$. When a user jumped forward, the distance gain was applied to a horizontal movement, and the virtual camera in VR was moved by the vector $d_{virtual} = g_d \times d_{real}$. We investigated the influence of the width of the alleys on the DT of distance gains in RDJ.

3.2.2 Height gains in RDJ

Height gain is the gain in the vertical direction and does not exist in the redirected wing. We denote the vertical position changes of the user in the real world as h_{real}. The position changes of the virtual camera in the vertical direction $h_{virtual}$ in the VR world are matched one by one using the position of the user in the real world. The ratio between h_{real} and h_{real} is the height gain: $g_h = h_{virtual}/h_{real}$. When a user jumps up, the height gain is applied to a vertical movement. The virtual camera in VR is moved by the vector $h_{virtual} = g_h \times h_{real}$. We explored the effect of the width of the alleys on the DT of height gains in RDJ.

3.2.3 Rotation gains in RDJ

In the real world, the head rotation of the user is represented by a vector containing three angles: pitch, yaw, and roll. The change in the direction of these vectors was mapped to a virtual camera. The yaw angle of rotation of the real-world head and virtual camera are denoted as r_{real} and $r_{virtual}$, respectively. The ratio between r_{real} and $r_{virtual}$ is defined as the rotation gain $g_r = r_{virtual}/r_{real}$. When a user jumps rotationally, the rotation gain is applied to a rotational movement. The virtual camera in VR is rotated by the vector $r_{virtual} = g_r \times r_{real}$. We examined the influence of the width of the alleys on the DT of rotation gains in RDJ.

4 Experimental study

4.1 Study design

We conducted 18 experiments to investigate the effects of the alley width on the DT when users jump in VR. These experiments were divided into six parts according to the width of the alley. In the experiments, we chose the minimum width of the alley as 1.0m. When the width of alley was 40m, the participants could no longer feel the influence of the wall. Therefore, we considered alley widths of 1, 2, 8, 16, 24, and 40m. We measured the range of the DT of distance gain (g_d), height gain (g_h), and rotation gain (gr) perceived by the participants.

In addition, we collected responses (larger/small) for all experiments using 2-AFC tasks. We statistically analyzed the data using 2D psychometric function fittings[5,8,10,27]. Based on our previous study on RDW and RDJ, we defined the point of subjective equality (PSE) as the value when 50% of the responses of the users were "longer." The "longer" means that the distance/height/rotation the user perceives in VE is greater than the actual distance. Moreover, we defined the DTs as the gain where 25% and 75% of the responses of the participants were longer. The range of gain was calculated from the absolute value of the difference in the DTs. Within this range, manipulating the jump distance, height, and rotation is hardly noticeable for the participant.

Because participants were prone to fatigue owing to repeated jumping during the experiments, the experiments were divided into multiple groups. Participants completed the simulator sickness questionnaire (SSQ) [28], which measured subjective simulator sickness after completing an alley-width experiment. Participants were asked to take a day off between experiments. Each experiment took one and a half hours and the entire test duration was three days.

4.2 Hardware and software

All tasks were performed in a 4m×4m laboratory. We used an HTC Vive system with a tracked HMD, three external trackers, and two wireless handheld controllers, as shown in Figure 1. The HMD was connected to a desktop PC (Intel Core i7 processor, 16 GB RAM, and NVIDIA 1080-ti graphics card). The virtual scene was rendered using OpenGL at 90 fps for each eye. The wireless hand-held controller was employed as an input device, and the participants used the handle to judge their actions.

4.3 Participants

A total of 16 participants (10 men and 6 women) were included in our user study, including 12 students. Participants were between 20 and 30 years of age (M=24, SD=4). We recorded the height of participants (M=171.4cm, SD=5.6). Twelve participants used immersive VR applications. In addition, the vision of participants was normal or corrected, and none of them reported vision or balance disorders. Two of the participants jumped in a VE using HMD.

4.4 Task 1: Distance relocation

In this task, we investigated whether the alley width affects the user perception of the horizontal jump distance. From the results of a previous study, the gain was controlled from 0.6 and 1.4 in intervals of 0.1[5,10]. When a user jumped forward, the distance gains were randomly selected and applied to the distance movement of the user. After each jumping, each user answered whether the perceived distance was greater or less than the actual jumping distance.

4.4.1 Design and procedure

Each participant completed 324 trials (9 gains × 6 repetitions × 6 widths), which consisted of 12 sets of 27 trials in a randomized order. We divided task 1 into 12 experimental phases in accordance with the width of the alley. The width of each alley was randomly divided into two experimental phases.

The participants were first informed regarding the experiment and asked to sign an informed consent form. Subsequently, they filled out the SSQ and a short questionnaire. Next, they moved to the VR workspace, put on the HMD and tracker, and learned how to hold the controller and use the controller to enter answers. Participants were required to stand inside the black circle of the VE every time they entered the VE, as shown in Figure 2.

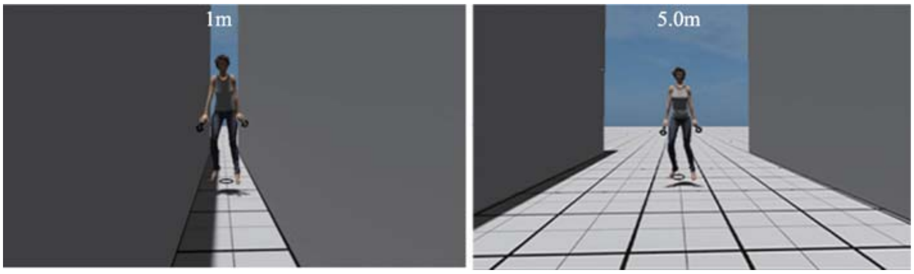

Figure 2 Avatar jumping forward in alleys with different widths. Movement of the avatar was redirected with distance gain. The avatar was driven by the position information of the participant's head, hands, waist, and feet.

After entering the VE, the participants first performed the practice phase, in which they were required to jump 0.8m to the blue line, which was positioned away from them in the VE. The primary purpose of the practice phase was to give participants the experience of jumping of 0.8m and having a distance gain of 1.0. To eliminate the influence of other factors, we used a simple scene for testing—a ground plane and two walls, where the grid texture was mapped on the ground and walls, and the grid lines were separated by 0.5m intervals, as shown in Figure 2. After each jump forward, the participants returned to the starting point of the virtual scene (a black circle) and prepared for subsequent experimental phases, as shown in Figure 2.

After completing these three exercises, the experimental phases begun. Each phase included 27 experiments. Participants filled in the SSQ questionnaire every time they completed the alley width experiment. At this stage, there were no 0.8m blue lines in the VE. The participants were asked to jump forward 0.8m according to their judgment. After the participants completed a forward jump, they answered the question: "Did you make a shorter or longer distance in the VE compared to the actual distance?" Participants used the controller to enter their answers and then used it to initialize the scene. Finally, they were asked to walk back to the black circle of the virtual scene and prepare for the next jump.

4.4.2 Results

The system could not detect 176 out of 5184 jumps. We deleted these undetected data and adjusted them using a psychometric function in the form of $F(x) = 1/(1 + b \times e^{-ax})(a,b \in R)$. Figure 3 shows the fitted psychometric function curve under different alley widths, where ∞ m represents the psychometric function under the floor scene only. We obtained the DTs, PSE, and R^2 (coefficient of determination) from the fitted psychometric functions in Figure 3, as shown in Table 1.

Table 2 presents the mean and standard deviation (SD) of the SSQ questionnaire in Task 1. BE is the result of the SSQ before the experiment. The SSQ results of the corresponding alley width after the experiment are 1, 2, 8, 16, 24, and 40m. We evaluated the scores of the groups using the paired-sample *t*-test and found no significant differences between them ($p>0.05$). In addition, SSQ scores usually increase over time; however, the increase was mainly owing to fatigue and sweating. Some participants complained of simulator sickness throughout the experiments. During the trial period, the participants did not report any form of discomfort.

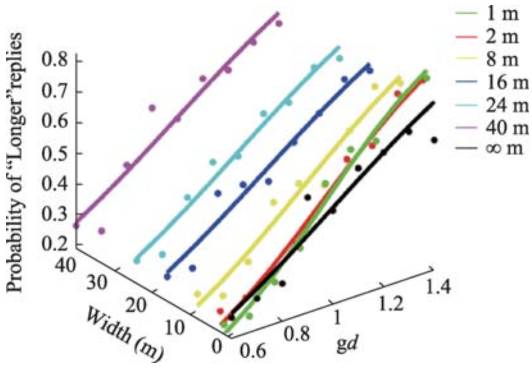

Figure 3 Fitted psychometric functions in Task 1. Fitting curves in the corresponding alley widths of 1m, 2m, 8m, 16m, 24m, and 40m. The ∞ m virtual scenes have only one plane (floor).

Table 1 DTs (0.25 and 0.75), PSE, range of distance gain, and R^2

	0.25	PSE	0.75	Range	R^2
1m	0.7015	0.9909	1.2803	0.5788	0.9728
2m	0.6722	1.0014	1.3307	0.6585	0.9758
8m	0.6397	1.0145	1.3893	0.7496	0.9331
16m	0.5373	0.9788	1.4204	0.8831	0.9212
24m	0.5583	0.9904	1.4226	0.8643	0.9449
40m	0.5515	0.9915	1.4314	0.8799	0.8729

Table 2 SSQ of Task 1 results

	BE	1	2	8	16	24`	40
Mean	2.58	6.10	7.8	17.21	11.86	11.56	8.80
SD	2.52	2.66	2.46	4.80	4.44	4.28	2.60

After the experiment, we conducted a brief interview with each participant. We found that most participants predicted the distance by observing the grid lines close to the landing. Some participants observed the speed of the PoV transition. When the alleys were narrow, they did not experience any discomfort.

4.4.3 Discussion

To study the relationship between the wall width and DTs, we listed the data in Table 1. Figure 4 demonstrates that the range of the imperceptible distance gains in RDJ is not related to the width of alley. According to our interviews, the participants judged the jump distance based on the grid on the ground, ignoring the two walls. Therefore, the alley width does not affect the distance gain in RDJ. Additionally, we found that when jumping in VR, we could ignore the influence of the occlusion distance on the distance gain. Consequently, in the design of an RDJ in VR, the influence of distance occlusion on the DT of the distance gain can be ignored.

4.5 Task 2: Height relocation

In this task, we investigated the effects of the alley width on the user's perception of vertical jump height. When a user jumped, the height gains were randomly selected and applied to the vertical movement of the user. After each jumping task, each user described whether the perceived height was greater or less than the

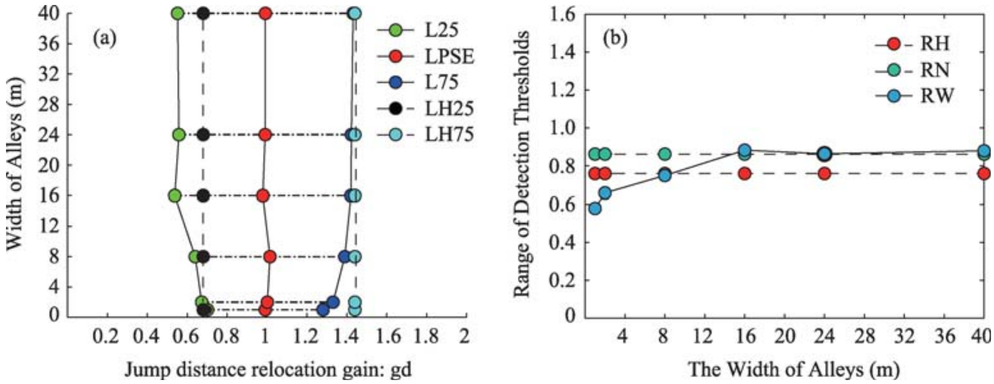

Figure 4 (a) Relationship between the width of alley, DTs, and PSE. The value in L25 is the small value of DTs. The value in LPSE is the PSE. The value in L75 is the larger value of DTs. The values in LH25 and LH75 are from RDJ[10]; (b) Relationship between the width of alley and the range of gain. RH is the range of gain from RDJ[10], and RN is the range of gain in an empty plane in our task. RW is the range of gain in each alley width.

actual jumping height.

4.5.1 Design and procedure

Each participant completed 252 trials (7 gains × 6 repetitions × 6 widths), consisting of 12 sets of 21 trials in a randomized order. We divided Task 2 into 12 experimental phases in accordance with the width of the alley. The width of each alley was divided into two phases. The gain was controlled from 0.25 to 1.75 in intervals of 0.25 based on an existing study[10]. After entering the VE, the participants first performed the practice phase, in which they were required to jump to a blue line 0.2m away from their head in the VE. The primary purpose of the practice phase was to acclimatize participants to jumping up 0.2m and reaching a height gain of 1.0. To eliminate the influence of other factors, we used a straightforward scene for testing: a ground plane and two walls, where the grid texture was mapped on the ground and walls, and the grid lines were separated by 0.5 intervals, as shown in Figure 5. After each jump, the participants returned to the starting point of the virtual scene (a black circle), as shown in Figure 5 and prepared for experimental phases.

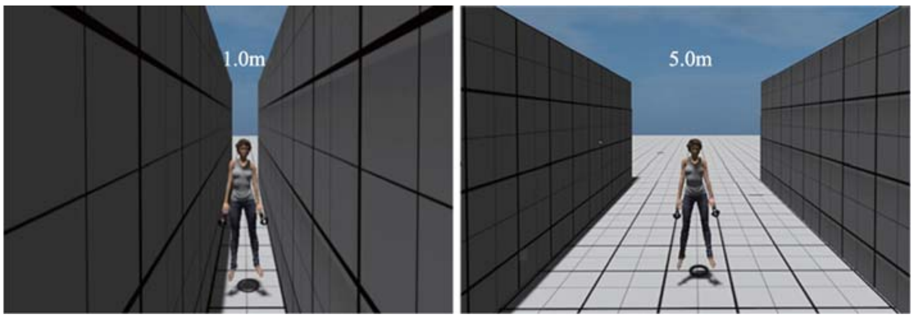

Figure 5 Avatar jumping in alleys with different widths. Movement of the avatar was redirected with height gain. The avatar was driven by the position information of the participant's head, hands, waist, and feet.

After completing these three exercises, 12 experimental phases were performed, each of which included 21 experiments. Participants were required to complete the SSQ questionnaire every time they completed an alley-width experiment. At this phase, there were no 0.2m blue lines in the VE. Participants were asked to jump 0.2m according to their judgment. After the participants completed a jump in the vertical direction, they first answered the question: "Did you make a smaller or larger jumping height in the VE compared to the actual height?" Participants used the controller to enter their answers and then used it to initialize the scene. Finally, they were asked to walk to the black circle of the virtual scene and prepare for the next jump.

4.5.2 Results

The system could not detect 156 out of 4032 jumps. Therefore, we deleted these undetected data and adjusted them with mental functions in the form of $F(x) = 1/(1 + be^{-ax})(a, b \in R)$. Figure 6 presents the fitted psychometric function curve under different alley widths, where ∞ m represents the psychometric function under the floor scene only. We obtained the DTs, PSE, and R^2 from the fitted psychometric functions in Figure 6, as listed in Table 3.

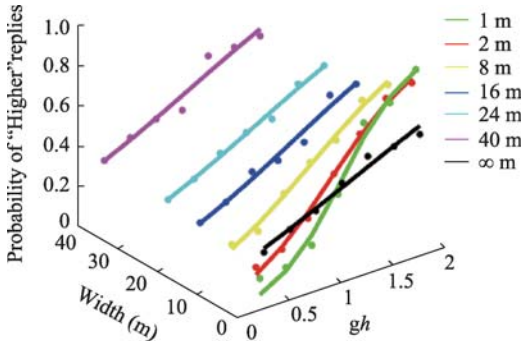

Figure 6 Fitted psychometric functions in Task 2. Fitting curves in the corresponding alley widths of 1, 2, 8, 16, 24, and 40m. The ∞ m virtual scenes have only one plane (floor).

Table 4 presents the mean and SD of the SSQ questionnaire in Task 2. BE is the result of SSQ before the experiment. The SSQ results of the corresponding alley width after the experiment are 1, 2, 8, 16, 24, and 40m. We evaluated the scores of groups using the paired-sample *t*-test and found no significant differences (p>0.05). During the trial period, the participants did not report any discomfort.

Table 3 DTs (0.25 and 0.75), PSE, range of height gain, and R^2

	0.25	PSE	0.75	Range	R^2
1m	0.7145	1.0374	1.3603	1.4085	0.9749
2m	0.5090	0.9641	1.4192	0.98	0.9894
8m	0.3768	1.0089	1.6411	0.4345	0.9848
16m	0.2611	1.1393	2.0175	0.5404	0.9463
24m	0.1343	1.1039	2.0736	0.6035	0.9814
40m	0.1125	1.0995	2.0866	0.7912	0.8974

Table 4 SSQ of Task 2 results

	BE	1	2	8	16	24	40
Mean	2.14	4.17	8.08	10.03	13.09	11.43	12.62
SD	2.58	3.42	3.80	5.71	6.05	5.14	4.81

After the experiment, we conducted a brief interview with each participant and found that some participants predicted the jumping height and made longer/shorter judgments by watching a near grid line on the wall during jumping. Many studies have monitored the speed of PoV transition. Moreover, when the alleys were particularly narrow, the participants did not feel discomfort.

4.5.3 Discussion

To study the relationship between the wall width and DTs, we present the data in Table 3. Figure 7 shows that when the width of alley is less than 24m, the height gain is negatively correlated with it. When the width of alley is greater than or equal to 24m, the height gain is no correlation with it. The height gains are less than the results achieved in a previous study[10]. Therefore, the width of alley affects the height gain of RDJ in our study and causes the height gain to be smaller than the previously reported results[10]. Therefore, considering the influence of the occlusion distance on the jump redirection height gain in designing RDJ is recommended. Within a specific range of the occlusion distance, the smaller the occlusion distance, the

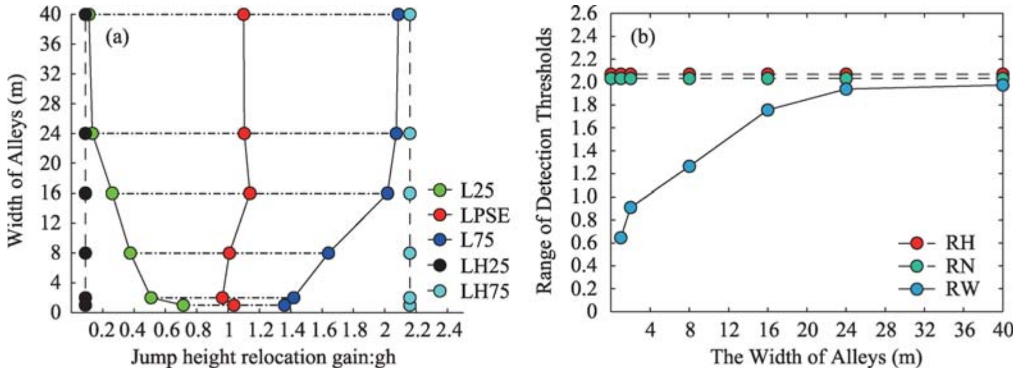

Figure 7 (a) Relationship between the width of alleys, DTs, and PSE. The value in L25 is the smallest value of DTs. The value in LPSE is the PSE. The value in L75 is the largest value of DTs. The values in LH25 and LH75 are from RDJ, respectively[10]; (b) Relationship between the width of alley and range of gain. RH is the range of gain from RDJ[10], and RN is the range of gain in an empty plane in our task. RW is the range of gain in each alley width.

smaller is the manipulation range of the height gain. Because our experimental results were achieved using six widths, designers can choose the following scheme for height gain: taking the occlusion distance as the *Y*-axis value and finding the corresponding two *X*-axis values shown in Figure 7a. These two *X*-axis values represent the DTs.

4.6 Task 3: Rotation relocation

In this task, we investigated the effects of the alley width on the user's perception of the jump rotation angle. When the user jumps rotationally, the rotation gains were randomly selected and applied to the rotational movement of the user. After each jumping task, each user answered whether the perceived rotation angle was greater or less than the actual jumping rotation angle (7 gains × 6 repetitions × 6 widths).

4.6.1 Design and procedure

Each participant completed 252 trials (7 gains × 6 repetitions × 6 widths), which consisted of 12 sets of 21 trials in a randomized order. We divided Task 3 into 12 experimental phases according to the width of the alley. The width of each alley was divided into two phases. The gain was controlled from 0.7 to 1.3 in intervals of 0.1 based on an existing study[10].

Practice and experiment phases were present in Task 3. In the practice phase, participants were required to rotate 90° while jumping rotationally. They followed an instruction line on the ground to turn 90° in the VE. After each jumping, the participants returned to the starting point of the virtual scene (a black circle), as shown in Figure 8, and prepared for subsequent experimental phases.

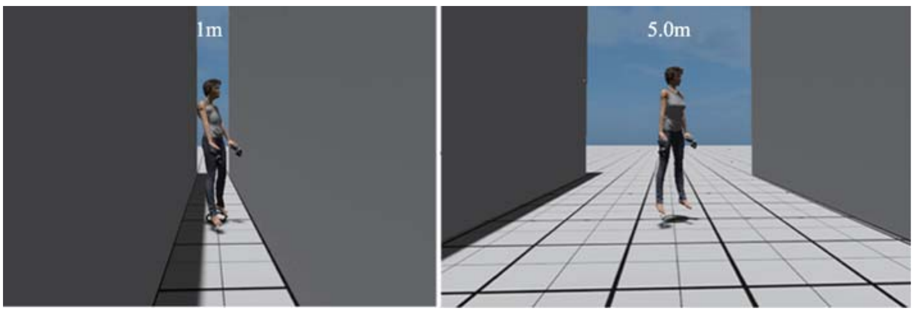

Figure 8 Avatar jumping rotationally in alleys with different widths. Movement of the avatar was redirected with the rotation gain. The avatar was driven by the position information of the participant's head, hands, waist, and feet.

4.6.2 Results

The system could not detect 163 out of 4032 jumps. Therefore, we deleted these undetected data and adjusted them with mental functions in the form of $F(x) = 1/(1 + b \times e^{-ax})$ (a,b in R). Figure 9 shows the fitted psychometric function curve under different alley widths, where ∞ m represents the psychometric function under the floor scene only. We obtained the DTs, PSE, and R^2 from the fitted psychometric functions in Figure 9, as listed in Table 5.

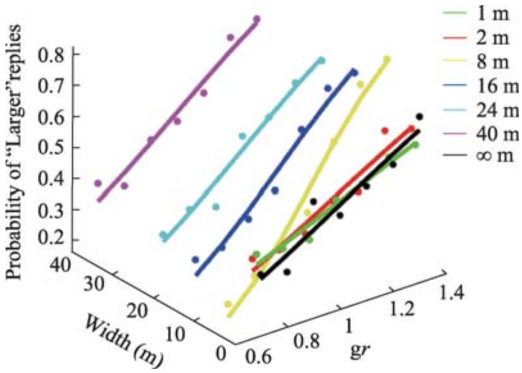

Figure 9 Fitted psychometric functions in Task 3. Fitting curves in the corresponding alley widths of 1, 2, 8, 16, 24, and 40m. The ∞ m virtual scenes have only one plane (floor).

Table 6 shows the mean and SD of the SSQ questionnaire in Task 3. BE is the result of SSQ before the experiment. The SSQ results of the corresponding alley width after the experiment are 1, 2, 8, 16, 24, and 40m. We evaluated the scores of the groups using the paired-sample *t*-test and found no significant differences ($p > 0.05$). During the trial period, the participants did not report any discomfort.

Table 5 DTs (0.25 and 0.75), PSE, range of rotation gain, and R^2

	0.25	PSE	0.75	Difference	R^2
1m	0.2612	1.009	1.7569	1.4957	0.8948
2m	0.4437	0.9911	1.5485	1.1148	0.8680
8m	0.7998	1.0122	1.2245	0.4247	0.9746
16m	0.7150	1.0209	1.3269	0.6119	0.9551
24m	0.6340	1.0028	1.3715	0.7375	0.9371
40m	0.6145	1.0012	1.3879	0.7734	0.9297

Table 6 SSQ of Task 3 results

	BE	1	2	8	16	24	40
Mean	3.29	7.45	19.60	20.00	17.99	12.70	15.6
SD	2.75	3.61	8.33	9.35	8.24	7.06	8.45

After the experiment, we conducted a brief interview with each participant and found that when the width of alley was 1 or 2m, and it was difficult for participants to determine which was larger. Many participants were required to watch the grid on the ground and then answer the questions. When the width of alley was 8, 12, and 20m, most participants watched the PoV transition speed. Moreover, when the alleys were particularly narrow, the participants did not feel any discomfort.

4.6.3 Discussion

To study the relationship between the width of the wall and DTs, we listed the data in Table 6. Figure 10 shows that the imperceptible range of rotation gain in RDJ is inversely proportional to the alley width when it is less than 8m and is proportional to the width of alleys in the range of 8−24m. When the width of alley is greater than 24m, the rotation gains are not related to the width of alley. Simultaneously, when the width of alley is 1.0 or 2.0m, the DT range is larger than in the previous cases, which enables us to explore larger virtual spaces more naturally. Therefore, the influence of the occlusion distance on the rotation gain of the jump redirection should be considered during the design process. This result reveals that when the occlusion distance is less than 2m, designers can use the RDJ rotation gain to jump in a larger physical

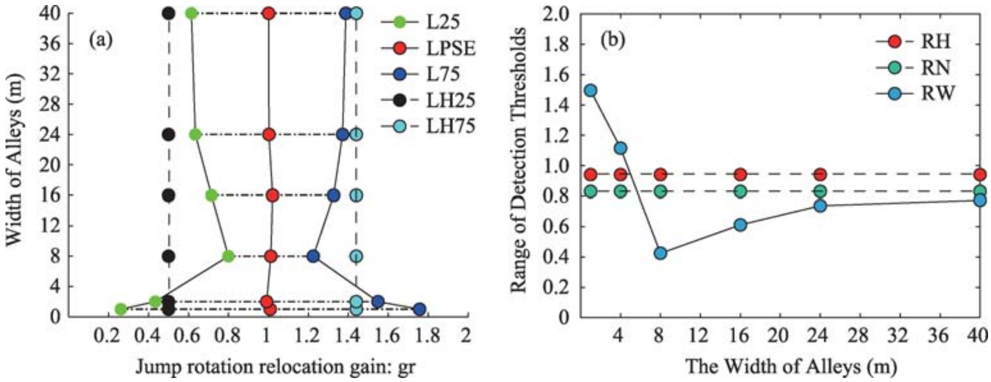

Figure 10 (a) Relationship between the width of alleys, DTs, and PSE. The value in L25 is the smallest value of DTs. The value in LPSE is the PSE. The value in L75 is the largest value of DTs. The values in LH25 and LH75 are from RDJ, respectively[10]; (b) relationship between the width of alley and the range of gain. RH is the range of gain from RDJ[10], and RN is the range of gain in an empty plane in our task. RW is the range of gain in each alley width.

tracking space. However, when the occlusion distance is greater than 2m, the manipulation range of the rotation gain decreases. Because our experimental results were achieved using six widths, the designer can choose the following scheme to obtain the rotation gain: use the occlusion distance as the *Y*-axis value, and find the corresponding two *X*-axis values as shown in Figure 10a. These two *X*-axis values represent the DTs.

5 Limitations and future work

In this study, we explored the influence of the width of alley on the DT in RDJ. In addition, this was a preliminary study of the factors affecting the DT in RDJ. The limitations of this study are as follows:

First, we only considered the effect of the width of alley scene on the DT in RDJ but did not consider the effect of different types of alleys on the DT. There are many types of alleys in VEs, such as lanes, paths, passages, and avenues. In the future work, we will explore the influence of various alleys on the DT in RDJ. In addition, we did not consider the influence of complex textures in the alley on DTs. This is an important factor that needs to be examined in the future.

Second, there are many scenes in addition to the alley scenes, such as rooms, different terrains, and 360° panoramic video. Therefore, further studies are required to investigate the effects of these scenes on the DT in RDJ. In the future, our work will explore the influence of panoramic videos and VE on DTs in RDJ.

Third, when we explored the effect of alley width on DTs, participants always stood in the middle of the alley, and we did not consider the condition under which the participants were not standing in the middle of the alley. Future work will better guide VR applications using our experimental results.

6 Conclusions

We studied the influence of the semi-occlusion environment on DTs in RDJ. We designed six alleys with different widths and conducted a user study on the manipulation range of distance, height, and rotation gains. Our results showed that the manipulation range of the distance gain in RDJ did not correlate with the alley width. The manipulation range of the height gain was negatively correlated with the alley width and was smaller than the results achieved in previous studies. When the width of alley was less than 2m, the manipulation range of the rotation gain was larger than that reported in existing studies. However, when it was greater than 2m, the width of alley in the manipulation range of the rotation gain was negatively correlated and smaller than the results reported in previous studies. We obtained the relationship between the occlusion distance and manipulation range of the three RDJ gains in complex environments and provided the guiding principles for selecting the three gains in RDJ. These findings were combined with other redirection technologies to provide a natural and rich VR experience.

Declaration of competing interest

We declare that we have no conflict of interest.

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