·**Article**·

Effects of virtual environment and self-representations on perception and physical performance in redirected jumping

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Abstract **Background** Redirected jumping (RDJ) allows users to explore virtual environments (VEs) naturally by scaling a small real-world jump to a larger virtual jump with virtual camera motion manipulation, thereby addressing the problem of limited physical space in VR applications. Previous RDJ studies have mainly focused on detection threshold estimation. However, the effect VE or self-representation (SR) has on the perception or performance of RDJs remains unclear. **Methods**   In this paper, we report experiments to measure the perception (detection thresholds for gains, presence, embodiment, intrinsic motivation, and cybersickness) and physical performance (heart rate intensity, preparation time, and actual jumping distance) of redirected forward jumping under six different combinations of VE (low and high visual richness) and SRs (invisible, shoes, and human-like). **Results** Our results indicated that the detection threshold ranges for horizontal translation gains were significantly smaller in the VE with high rather than low visual richness. When different SRs were applied, our results did not suggest significant differences in detection thresholds, but it did report longer actual jumping distances in the invisible body case compared with the other two SRs. In the high visual richness VE, the preparation time for jumping with a human-like avatar was significantly longer than that with other SRs. Finally, some correlations were found between perception and physical performance measures. **Conclusions**   All these findings suggest that both VE and SRs influence users' perception and performance in RDJ and must be considered when designing locomotion techniques.

Keywords   Virtual reality; Virtual locomotion; Redirected jumping

1 Introduction

The demand for immersive experience in virtual reality (VR) continues to increase. To move in a virtual environment (VE), bipedal human walking offers users the most natural interaction with the VE[1,2]. However, users may hit obstacles and become interrupted or even encounter safety issues when exploring a large VE within a limited physical space. To solve these problems, various locomotion techniques have been proposed, including walking-in-place (WIP)[3,4], joystick-based locomotion[5,6], teleportation[5-7], and redirected walking (RDW)[6,8,9]. Other locomotion techniques such as trigger walking[10] and omnidirectional treadmills[11-13] are also useful alternatives. Among these, RDW is relatively cheaper than walking on omnidirectional treadmills and offers users more natural walking experiences. Some RDW methods delete manipulate imperceptibly manipulate users' viewpoints while walking, but these methods require estimations of detection thresholds for various gains[14] .
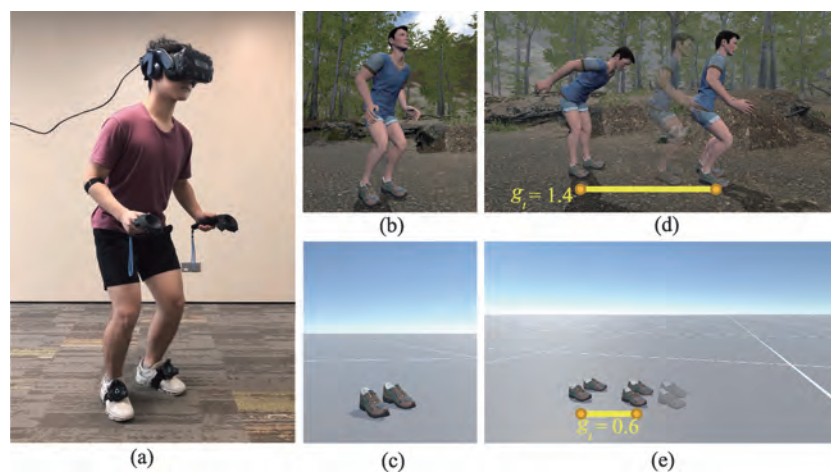

Figure 1   Illustration of the experimental conditions to study the effects of virtual environment (VE) and self-representations (SRs) on redirected jumping. (a) User initiates a one-time two-legged takeoff forward jumping action in the real world; (b) VE and SR under the HighVisuals and HumanAvatar condition; (c) VE and SR under the LowVisuals and Shoes condition; (d) Illustration of ready and landing status of an enhanced jump with translation gain $g_t = 1.4$ (under the same condition as in (b)); and (e) illustration of an attenuated jump with translation gain $g_t = 0.6$ (under the same condition as in (c)). The translucent SRs in (d) and (e) indicate unmodified jumps with $g_t = 1.0$.

With the popularity of wearable VR devices, VR locomotion techniques have been applied not only to walking, but also during jumping. A novel redirected jumping (RDJ) technique for the one-time two-legged takeoff jump in VR has recently been proposed[15]. In a jumping procedure, parameters such as horizontal distance, height, and rotation angles can be manipulated imperceptibly if the corresponding gains do not exceed the detection thresholds.

According to Kruse et al.[16], users rely heavily on the visual cues of the VE and the modeling of the feet to perceive the manipulation of translation gains in the RDW. For jumping motion, we observed that a jump in the real world usually starts with a preparation procedure in which users typically observe the surrounding environment or swing their bodies to adjust their balance and power. Furthermore, users may perceptually measure the jumping distance by determining their position in the environment after landing on the ground.

This paper reports the comprehensive user study we conducted to investigate the effects of VE and self-representations (SRs) on the perception and physical performance of RDJs. Visually simple and rich scenes were built to test the VE. Meanwhile, with trackers bound to body joints, the virtual body was visualized in

real time as either an invisible body, a pair of shoes, or a human-like avatar.

This resulted in six conditions under which recruited participants were asked to complete one-time forward jumps for a certain distance. Based on objective experimental data and subjective survey results, we confirmed that VE and SR can affect the performance and perception in RDJ. The main contributions of this work are:

• We designed VE conditions that offer low-and high-level visual richness and SR conditions with different virtual body visualizations, and conducted a within-subject pseudo-two-alternative forced-choice (pseudo-2AFC) experiment in RDJ.

• We report the correlation results in objective and subjective measures and provide new insights into future VE and SR design in RDJ.

2   Related work

2.1   Gain perception for redirected walking

Among VR locomotion techniques, real walking has significant advantages in simplicity, straightforwardness and naturalness over alternatives such as walking in place and flying[17]. Limited physical space poses a challenging or even impossible task for a user to walk freely in a large VE without any redirection techniques. To make it possible for users to experience a large VE without losing immersion, RDW, a common and useful redirection technique, is often applied to manipulate a player's movement[2,8,9,18−21] or the VE architecture[22−26]. Some RDW techniques[9,19−21,27,28] are based on imperceptible manipulations of a user's point of view (PoV) in a VE while walking in the tracking area, where each manipulation is a scaling ratio (i.e., gain) imposed on the attributes of the walking path. In addition, reinforcement learning-based RDW methods have been proven to be efficient, even for multiple users[29−31].

Gains for virtual walking manipulation can be classified into four types: rotation gain manipulates the rotation angle of the user, translation gain manipulates the walking distance on a straight line, curvature gain bends a straight walking line[9], and bending gain adjusts the curvature of a curved walking trajectory[32]. Between the physical and virtual distance manipulated by gains, user studies based on pseudo-2AFC tasks and psychometric curve fitting techniques were commonly conducted[9] to test whether participants can tell the difference between walking in the real world and walking in a virtual environment manipulated by different gains. For instance, Steinicke et al.[9] and Langbehn et al.[32] employed methods to estimate the detection thresholds for translation, rotation, curvature, and bending gains. To determine whether the richness of the visual stimulus has an influence on the sensitivity to gains, Kruse et al. conducted a user study to measure the detection thresholds for translation gains by changing the visibility of virtual feet and the visual richness of the VE[16]. They found that the visual richness of the VE had a much greater influence on the user's gain perception than the SR visibility of the user's feet. Reimer et al. investigated the influence of full-body avatar on translation and curvature gains[33].

2.2   Virtual jumping and redirected jumping

Jumping, an important means of locomotion in daily life, is also common in the VR experience. Bolte et al. introduced a jumper metaphor to help users move larger distances in fully immersive virtual environments (IVEs)[34]. To use this locomotion method, users specify the target position for landing by looking at the target, then move toward the target with acceleration above a given threshold to activate the jumping procedure. According to their experiments, this method can provide more effective VE exploration

than real walking but may introduce slight disorientation effects.

Some studies have investigated virtual jumping in specific VR scenes[35−38]. Kim et al. designed a cable-driven system to manipulate the jumping and applied visual gains to simulate an experience of reduced gravity on the lunar and Martian surfaces in VR[36]. Kang et al. explored the combined effect of physical trajectory and visual gain manipulations, concluding that these manipulations can be applied simultaneously to solve the issue of space limitations[37]. To simulate skydiving in an immersive VR experience, Sasaki et al. proposed and implemented a system based on virtual super-leaping as a non-invasive, low-effect, and safe method[38].

Recently, redirected and augmented jumping have become hot topics in VR locomotion. The redirected jumping technique was first proposed by Hayashi et al. [15], in user studies, they measured thresholds of unnoticeable gains for horizontal and vertical translation and rotation. Jung et al. measured the perception of curvature gains in jumping by asking the user to jump in a VE with five raised pedestals[39]. The detection thresholds of RDJ have wider ranges than those of RDW, which means that an even smaller physical space suffices if we apply RDJ techniques instead of RDW. Wolf et al. conducted a study in a virtual Parkour scene comparing teleportation with scaled jumping and forward jumping, from which they concluded that most scaled jumping conditions could bring the user a higher sense of immersion and motivation without increasing simulator sickness[40].

2.3   Presence

Presence is the subjective feeling in which participants consider that they are virtually in one place, whereas in the real world, they are located in another place[41,42]. In VR, presence is a sense of "being there" in the VE instead of the real physical space[43], which means that a highly immersive VE can convince participants to believe they are actually located there.

Questionnaires such as the Witmer and Singer Presence Questionnaire (WS)[41], the Slater−Usoh−Steed (SUS) questionnaire[44], and the Igroup Presence Questionnaire (IPQ) [45] are the most common tools to measure presence after users' experiences in IVEs. In this study, we used the IPQ questionnaire to investigate the presence felt by participants in RDJ experiences.

2.4   Avatar and embodiment

In VR, self-representation is helpful to users' cognitive processes and can alleviate their mental loads in tasks[46−50]. On the contrary, the absence of a virtual body may lead to negative effects on perception and the disembodied phenomena[51,52]. Maselli et al. concluded that to produce full-body ownership, an avatar visualized from the first-person view can be employed to represent the participant's action in real time[53]. The sense of embodiment is usually measured by subjective questionnaires because of its versatility and ease of use. One of the most commonly used questionnaires to measure the sense of embodiment is the Gonzalez−Franco and Peck (GFP) embodiment questionnaire[49], which contains six main components (body ownership, agency and motor control, tactile sensations, location of the body, external appearance, and responses to external stimuli). Researchers can select applicable questions based on research objectives.

Peck et al. found that, under the same hand placement setup (proximal or non-proximal), the condition with avatar outperformed the one without avatar on GFP embodiment scores in Stroop interference tasks[54]. Fribourg et al. conducted experiments by asking users to match a given avatar configuration to help understand the inter-relations among the factors of avatar appearance, avatar control, and user point of

view[55]. The experimental results show that setting an optimal avatar configuration was unnecessary. Instead, a higher degree of control that provides a satisfying embodiment experience would be preferred. Inspired by this, we measured embodiment perception with different SRs in RDJ.

3   Redirected jumping

3.1   Manipulation of jumping distance

Hayashi et al. [15] conducted experiments to measure he detection thresholds for translation, height, and rotation gains of the one-time two-legged takeoff jump. In this study, we focused mainly on the horizontal translation gain $g_t=d_{virtual}/d_{real}$, defined by the ratio of the horizontal jumping distance in the VE to its counterpart in the real world in a one-time two-legged takeoff jump.

In our experiment, the value of the translation gain g_t was chosen within a pre-defined range before each forward jump, and was applied to manipulate the user's point of view (PoV) during the jump. The virtual jumping distance $d_{virtual}=g_t\times d_{real}$ was correspondingly scaled according to the manipulation factor g_t.

3.2   Jumping detection

Real-time jumping detection is essential for manipulating the jumping parameters in RDJ. According to previous RDJ work[15,39], a jumping action can be divided into five phases, namely, standing, ready, ascending, descending, and landing.

• Standing: The user stands upright and remains stationary. The standing phase transition to the ready phase if the user lowers his or her head and waist but can also transition from landing phase.

• Ready: The user bends at their knees with their feet kept on the ground. The user can transition from the ready phase back to the standing phase by standing upright, or transition to the ascending phase when the positions of the user's head and waist move upward while the feet leave the ground.

• Ascending: In this phase the positions of the user's head, waist, and feet move upward in the air. This phase transitions to descending phase when the corresponding positions start moving downward.

• Descending: After ascending, the user descends in the air.

• Landing: The user lands on the ground after descending. If the user stands upright after landing, the user transitions to the standing phase.

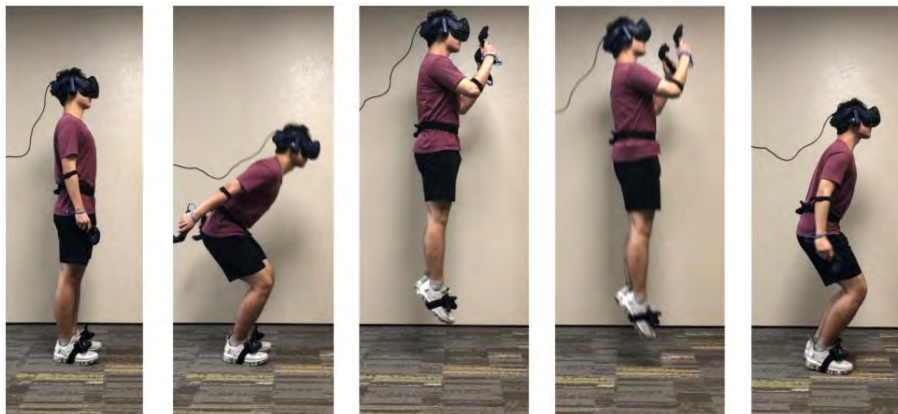Figure 2 illustrates the jumping phases. In our experiment, all jumping trials were limited to one-time

Figure 2   Illustration of the five jumping phases. From left to right: Standing, Ready, Ascending, Descending, and Landing.

two-legged takeoff jumping, and the scaling of virtual jumping distance was applied during the ascending and descending phases.

4　Experiments

In this section, we present the details of the experiment for measuring the physical performance and perception in RDJ with horizontal translation gains under various VE and SR conditions. We tested VEs of two visual richness levels, in which one is a simple scene with low visual richness, and the other is a photorerealistic outdoor scene with high visual richness. Three SR conditions were tested: fully transparent body, human-like avatar, and a representation that only shows the shoes of the user. In total, six combinations of avatar and VE conditions were tested, from which we collected objective data of physical performances and the participant's subjective perception of jumping manipulation, feeling of presence, intrinsic motivation, and responses to the embodiment questionnaire. Both the VE and SR conditions were expected to affect a user's sensitivity to gain manipulations and other perception measures. More precisely, a high visual richness VE was anticipated to provide higher enjoyment and a better sensitivity to translation gains than a low-visual VE[16]. For SR conditions, the human like avatar was intended to provide higher enjoyment and better sensitivity to translation gains than those from shoe representations and invisible bodies. This assumption is based on the idea: that the human-like avatar, in providing full-body motion visualization, should lead participants to behave and perceive in the same way as if they were actually in the physical space. Therefore, we made the following hypotheses:

　• H1: The range of unnoticeable translation gains is smaller for a high visual richness VE than that for a low visual richness VE.

　• H2: The range of unnoticeable translation gains is smallest when the participant's body is represented as a human-like avatar.

　• H3: The sense of enjoyment is higher in the high visual richness VE than in the low visual richness VE, and highest with the human-like avatar among all self-representation types.

4.1　Participants

Fifteen participants were recruited to complete the experiment (12 males and 3 females, mean age: 25.73, SD=4.79; mean height: 172.53cm, SD=6.29cm). All were researchers or students from a local institute. All claimed to have no visual impairment and confirmed having good general physical conditions for conducting the study. As for VR experiences, two had no experience, nine had fewer than five experiences, and the rest had more than five experiences. Eight participants wore glasses when they took part in the experiment.

4.2　Apparatus

The experiment was conducted in a 4m×4m physical tracking space with a height of 2.5m. The experimental apparatus consisted of the head-mounted display (HMD) (HTC Vive Pro Eye headset, 1440× 1600 pixel resolution per eye, 110° diagonal field of view) weighing approximately 0.6kg, two hand-held controllers, and three additional trackers bound to the waist and feet. The 6-DoF poses of the HMD, controllers, and trackers were recorded by two HTC Vive Base Stations placed at the corners of the tracking space and mapped to the positions of the user's head, hands, waist, and feet. A Polar OH1+ optical heart rate sensor was used to record the heart rates of the participants.

　The RDJ system was implemented using Unity3D (ver. 2019.3.1f1) and SteamVR running on a PC with

an Intel Core i7-8700K 3.70GHz CPU, 16GB RAM, and NVIDIA GeForce RTX 2080 GPU. The Final IK plugin, an implementation of inverse kinematics, was used to infer the body pose of the human-like avatar from the recorded head, waist, hands, and feet poses. The HMD refresh rate was kept at 90Hz. During the experiment, a pair of headphones from the HMD was used to reduce the physical environment noise. The participants' safety was overseen by a staff person in the lab, and none of the participants fell or slipped during the experiment. The participants did not report any distraction from the physical world.

4.3 Experimental design and conditions

Following previous RDW and RDJ studies[9,15,16], a pseudo-two-alternative forced-choice (pseudo-2 AFC) method was used for the experiment design. The pseudo-2AFC was designed to avoid response bias when participants were asked to guess an answer. The two VE conditions tested were:

• Low Visual Richness (LowVisuals): A simple scene composed of a skybox and a ground plane, similar to the setting used by Hayashi et al.[15], and consisting of 5m×5m regular grids painted on the ground, as shown in Figure 3a.
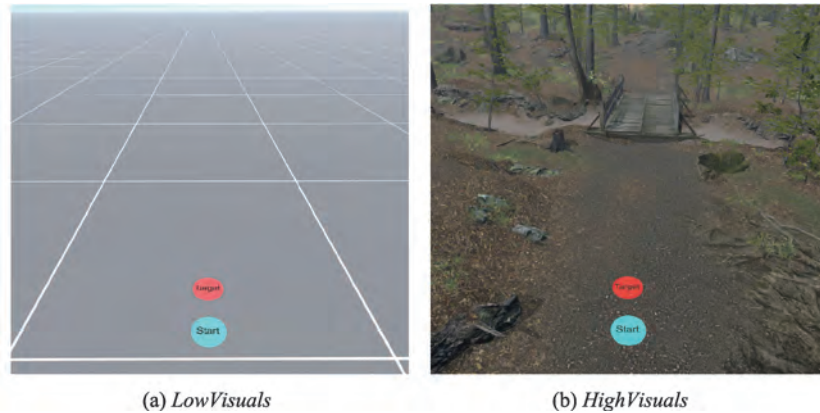

(a) *LowVisuals*   (b) *HighVisuals*

Figure 3   The two VEs used in our experiment. (a) LowVisuals; (b) HighVisuals. Start and target positions for jumping at the training stage are indicated by blue and red circles, respectively.

• High Visual Richness (HighVisuals): A scene of a forest with rich visual cues including bridges, trees, rocks, grasses, etc. The ground around the jumping area was guaranteed to be horizontally flat as shown in Figure 3b. For each VE condition, three SR conditions were tested:

• Invisible body (InvisibleBody): A fully transparent body.

• Shoe representation (Shoes): A pair of shoes were visible.

• Human-like avatar (HumanAvatar): a human-like avatar was chosen from the precreated male and female avatars, with the appearance modified based on the participant's size and skin color.

Based on the results from our pilot study, the 5m×5m regular grids format on the ground for low visual richness was chosen because this environment setting provides a few visual cues, and at the same time prevents participants from counting the grids to measure their jumping distances. To provide a better sense of reality, we set the sun elevation angle to 45° so that the shadow (with Shoes and HumanAvatar) was visible. As shown in Figure 4, six conditions were tested with nine discrete translation gains gt controlled from 0.6 to 1.4 in 0.1 increments[15,16] and repeated three times in random order. The order of VEs was randomized for each participant and counterbalanced across participants using a Latin square design. For each VE, three consecutive SR conditions were tested and counterbalanced across participants to mitigate possible learning effects. With a within-subject design, each participant finished six trial blocks (two VEs× three self-representations) with 27 trials (nine gains×three repetitions) in each block. In line with the
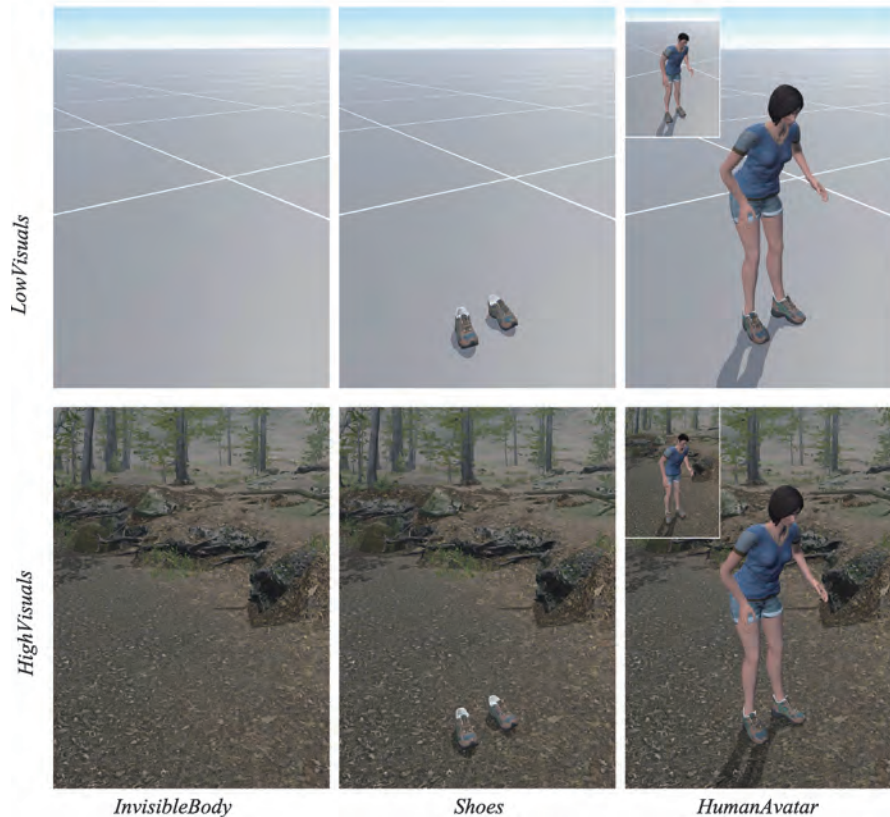
Figure 4   Illustration of combined VE and SR conditions in our experiment. Top: LowVisuals; Bottom: HighVisuals. Columns from left to right: InvisibleBody, Shoes and HumanAvatar (female and male).

setting of previous RDJ work[15], participants were asked to jump horizontally 0.8m, which did not incur a heavy physical load.

4.4   Measures

Both objective physical performance and subjective perception of participants were measured during the user study. The measured physical performance included preparation time prior to jumping, actual jumping distance, and heart rate intensity. Subjective perception measures were collected using questionnaires.

4.4.1   Objective performance measures

Preparation time for jumping. The performance of the user before a jump may also have an effect on the perception of jumping manipulation. Therefore, to evaluate whether conditions affect the jumping behavior, we recorded the preparation time for each jumping action. Specifically, after the participant walked back to the starting point and confirmed the next trial, time recording was begun until the participant's feet left the ground. The average preparation time for each condition was computed.

　Actual jumping distance. This metric was used to evaluate the effect of different combinations of conditions on the participant's jumping performance. Although the participants were asked to jump a 0.8m distance in the virtual world, the actual jumping distance may be affected by the VE and SR conditions. The actual jumping distance for each participant was recorded and the average actual jumping distance for each condition was computed.

　Heart rate intensity. Heart rate may be an objective metric associated with participant perception because the heart rate can reflect the participant's tension level. During the experiment, the heart rate of

each participant was recorded and the heart rate intensity was computed using the Karvonen formula[56] given by:

$$H = \left(H_{max} - H_{rest}\right)I + H_{rest},\tag{1}$$

$$I = \frac{H - H_{rest}}{H_{max} - H_{rest}},\tag{2}$$

where $I \in [0, 1]$, H is the average heart rate from the confirmation of the next trial to landing on the ground, $H_{max} = 220 - a$, where a is the participant's age, and H_{rest} is the participant's resting heart rate.

4.4.2 Subjective perception measures

Detection thresholds for gains. As mentioned before, the "longer" and "shorter" responses to the question, "Compared to the actual distance you jumped in the real world, was the distance in the virtual environment longer or shorter?" were collected. The psychometric function was estimated with an a-b core based on the proportion of "longer" responses, a and b are constants to be determined:

$$y = \frac{1}{1 + b \times e^{-ax}},\tag{3}$$

Lower detection threshold (LDT), point of subjective equality (PSE), and upper detection threshold (UDT) were measured at probability values of 25%, 50% and 75%.

Presence. The IPQ presence questionnaire[45] was answered by each participant after each trial block to evaluate the sense of presence experienced in a VE. The three sub-measures for the participant's feeling of presence include attention to the VE (spatial presence), involvement (involvement), and how real the VE seems (experienced realism), plus an additional general item (sense of being there) in the subjective questionnaire[57]. In total, 14 questions answered by participants were rated on a 7-point Likert scale from 0 to 6. The total presence score was computed as the average of the 14 scores.

Embodiment. A subset of questions from the GFP embodiment questionnaire[49] was used to evaluate the participant's sense of embodiment for each trial block. Specifically, the questionnaire contained four main components to evaluate Ownership, Agency, Location, and Appearance. The total embodiment score was computed within the range of [−3, 3] according to the calculation method suggested in[49] as (Ownership/3) × 2 + (Agency/3) × 2 + Location × 2 + (Appearance/2)/7. Please refer to[49] for details.

Intrinsic motivation. The intrinsic motivation inventory (IMI) scale[58] was conducted after each trial block to evaluate participant's intrinsic motivation. The 7-point Enjoyment and Tension Likert scales were used to evaluate enjoyment and tension perception.

Cybersickness. To measure cybersickness, the Simulator Sickness Questionnaire (SSQ)[59] was answered before (pre-SSQ) and after (post-SSQ) each trial block.

4.5 Procedure

The study was approved by the ethics committee of the local institute. Upon arrival at the lab, the participants read and signed an informed consent form containing written instructions about the experiment. Their height was measured and they were asked to fill out a demographic form, followed by a pre-SSQ questionnaire[59]. The details of the experiment were clearly explained to the participants. The participants were shown all three types of avatars and the gender, skin color, and size of the human-like avatar were set according to the participant's characteristics. The participants were then equipped with VR devices, followed by a 3-second calibration stage to record the initial positions of their head, waist, hands, and feet.

As mentioned previously, the order of VE conditions was randomized for each participant and counterbalanced across the participants. Under each condition, three blocks of trials corresponding to the

SR conditions were completed by each participant. For each trial block, a training stage was used to help the participant perceive the scene and understand how the RDJ functions. In the training stage, participant was asked to jump a distance of 0.8m from a blue start circle to the red target circle; both circles had a radius of 0.25m (Figure 3). Three training trials with horizontal translation gains g_t of 0.6, 1.0, and 1.4 known by the participant were experienced one by one. After each training trial, the VE and SR were temporarily hidden. Then, the participant followed guidance in the VE and walked back to the new starting position randomly chosen within a 0.5m range of the initial physical start position along the jumping direction. The randomization of the starting position avoids the participant from inferring the previous jumping distances by counting the walking steps. The participant then confirmed to start the next training trial via a UI. Subsequently, the VE disappeared then reappeared with the virtual starting position in the VE randomized around the initial virtual starting position within a 2m×2m area to prevent the participant from using fixed references (e.g., grids in LowVisuals condition) in the VE to measure distance among trials. The participants were aware of the randomization mechanisms.

After completing practice trials, a testing trial block containing 27 trials (nine gains × three repetitions) was begun without showing the start and target indicators. The participant confirmed ready for the jumping by pressing either button on the controllers, and then performed the jumping action. Two seconds after landing on the ground, a UI showed up on the HMD with the question: "Compared to the actual distance you jumped in the real world, was the distance in the virtual environment longer or shorter?" The choices "longer" and "shorter" were assigned to the left or right controllers counter- balanced in random order in advance for each participant and kept unchanged, with the aim of alleviating left- and right-handed bias. The participant could use the left or right controller to respond to the question. After answering the question, the participant walked back to the randomly positioned starting point and then entered the next trial. The participants were allowed to pause and break at any time. However, no participant asked for extra breaks during the experiment.

After finishing all trials in a trial block, the participant removed the HMD and filled out the post-SSQ[59] IMI[58], GFP[49], and IPQ[45] questionnaires on a PC. The participant took a break of at least 5min to calm their heart rate before the next block, then completed another Pre-SSQ questionnaire and started the next trial block. After filling out the last set of questionnaires, the participant was asked to remove all the mounted trackers and encouraged to leave open comments concerning the experiment. The average time that a participant spent in the experiment was approximately 100min, including the break time between trial blocks. The participants were thanked and paid for their participation.

5　Results

In this section, experimental results of objective performance and subjective perception are ana-lyzed. For each measure, a repeated measures analysis of variance (RM-ANOVA) at the 5% significance level was adopted. Mauchly's test was performed to verify the sphericity of the data and an RM-ANOVA with Greenhouse-Geisser correction was used if the sphericity was violated. Pairwise comparisons were conducted with Bonferroni adjustment. For cases where the data was not normally distributed (revealed by Kolmogorov-Smirnov tests), Friedman tests at the 5% significance level, and post-hoc Wilcoxon signed-rank tests were used instead.

5.1　Objective performance

Figure 5 shows the preparation time for jumping, actual jumping distance, and heart rate intensity.
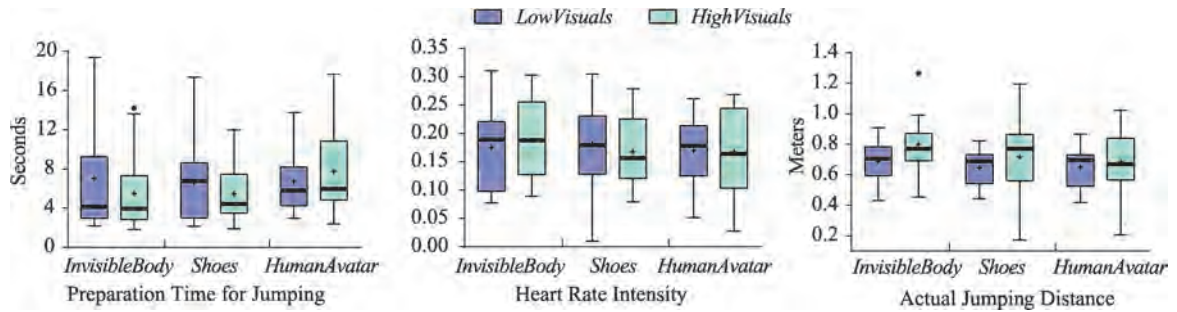
Figure 5 **Preparation time for jumping (seconds), actual jumping distance (meters), and heart rate intensity measurements in RDJ. The cross, the line across the box, and the dots represent the mean, the median, and the outliers, respectively.**

Preparation time for jumping. A Friedman test revealed a significant main effect of SR (p=0.015) under the HighVisuals condition. The post-hoc analysis indicated significant differences between HumanAvatar and Shoes (p=0.008) and between HumanAvatar and InvisibleBody (p=0.023).

Actual jumping distance. An RM-ANOVA revealed a significant main effect of SRs (F(2, 28)=5.83, p= 0.008, η^2=0.294). Post-hoc comparisons indicated that InvisibleBody had a significantly longer actual jumping distance than Shoes (p=0.028) and HumanAvatar (p=0.007). The actual jumping distances in LowVisuals VE were significantly smaller than the expected target distance (0.8m), with InvisibleBody: − 0.113, t(14)=−3.46, p=0.004; Shoes: −0.155, t(14)=−5.02, p<0.001; and HumanAvatar: −0.150, t(14)=− 4.64, p<0.001.

Heart rate intensity. No significant interaction effect was found between VE and SRs. No significant main effect of VE or SR was found, either.

5.2 Subjective perception

Detection thresholds for gains. Figure 6 shows the collected responses to translation gains and fitted psychometric function curves under the test conditions. The x-axis indicates the translation gain values and the y-axis indicates the probability of choosing the answer "longer" in pseudo-2 AFC tasks. For each gain value, the dots and corresponding bars indicate the mean values and the standard errors of corresponding response possibilities. Detection thresholds are highlighted in each plot. An RM-ANOVA indicated that no significant interaction effect was found between VE and SRs on detection thresholds. Pairwise analysis
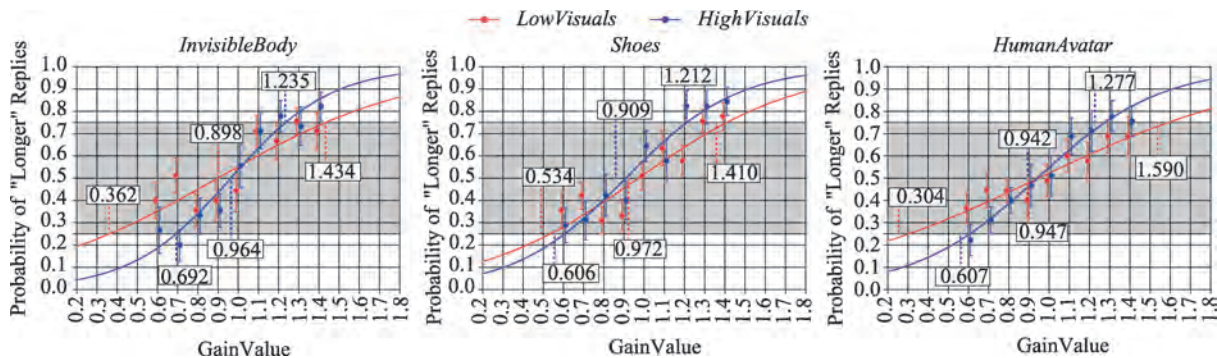

Figure 6 **Plotted results of discrimination between virtual and physical distances for different conditions. The x-axis shows the applied translation gains and the y-axis shows the probability of the participants' perception that they jumped further than in the real world. Detection thresholds corresponding to response probability of 25%, 50%, and 75% are highlighted.**

revealed significant differences between VE on LDT (p=0.041) and UDT (p=0.020). LDT in LowVisuals was significantly smaller than that in HighVisuals, whereas UDT in LowVisuals was significantly larger than that in HighVisuals, thus, confirming hypothesis H1. Nevertheless, no significant main effect of VE was found on PSE.

No significant main effect of SRs was found on the detection thresholds. Thus, hypothesis H2 was rejected.

Presence. Figure 7a shows the presence scores collected from the IPQ questionnaire. An RM-ANOVA showed that there was a significant main effect on IPQ presence between LowVisuals and HighVisuals with $F_{(1, 14)}$=28.92, p<0.001, η^2=0.674, where the presence score was significantly higher in HighVisuals than LowVisuals. Additionally, a significant main effect was found among the SRs ($F_{(2, 28)}$=8.79, p=0.001, η^2=0.386). Post-hoc comparisons indicated significant differences between InvisibleBody and Shoes (p=0.022), InvisibleBody and HumanAvatar (p=0.004), and Shoes and HumanAvatar (p=0.043).
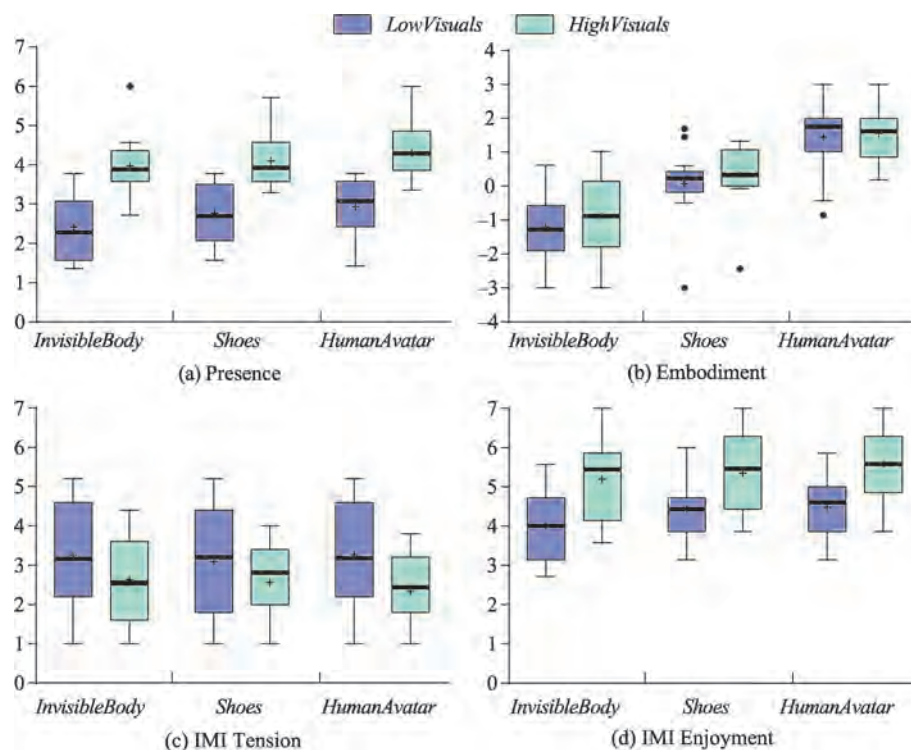

Figure 7   Subjective measurements of RDJ. (a) Presence[45]; (b) Embodiment[49]; (c) IMI Tension; (d) IMI Enjoyment[58]. The cross, the line across the box, and the dots represent the mean, the median, and the outliers, respectively.

Embodiment. Figure 7b shows the embodiment responses gathered from the GFP questionnaire. An RM-ANOVA revealed a significant main effect between LowVisuals and HighVisuals with $F_{(1, 14)}$=18.65, p=0.001, η^2=0.571. A significant main effect was also found among the SRs with $F_{(1.27, 17.75)}$=26.34, p<0.001, η^2=0.653. Post-hoc pairwise comparisons revealed significant differences between each pair of SR conditions: InvisibleBody and Shoes (p<0.001), InvisibleBody and HumanAvatar (p<0.001), and Shoes and HumanAvatar (p=0.006). Embodiment was highest with HumanAvatar and lowest with InvisibleBody.

Intrinsic motivation. Figure 7c and 7d shows the enjoyment and tension responses gathered from the IMI questionnaire. An RM-ANOVA indicated that VE ($F_{(1, 14)}$=10.90, p=0.005, η^2=0.483) had a significant main effect on IMI Tension. Regarding the responses to IMI enjoyment, significant main effects of VE ($F_{(1, 14)}$=25.34, p<0.001, η^2=0.644) and SRs ($F_{(2, 28)}$=12.54, p<0.001, η^2=0.472) were found. Post-hoc

pairwise comparisons revealed significant differences between InvisibleBody and Shoes (p=0.002), and between InvisibleBody and HumanAvatar (p=0.001). These results confirmed hypothesis H3: the IMI enjoyment score in HighVisuals was significantly higher than in LowVisuals, and was the highest with HumanAvatar among SRs. Table 1 lists the RM-ANOVA results of subjective measures.

Table 1　Analysis of IPQ[45], GFP[49], IMI Tension (IMI-T) and Enjoyment (IMI-E)[58] with RM-ANOVAs

Measure	Effect	df	F	η^2	p
IPQ	VE	1, 14	28.92***	0.674	< 0.0001
	SR	2, 28	8.79**	0.386	0.001
	VE×SR	1.32, 18.43	1.31	0.085	0.28
GFP	VE	1, 14	18.65***	0.57	< 0.001
	SR	1.27, 17.75	26.34***	0.653	< 0.0001
	VE×SR	1.34, 18.81	0.31	0.022	0.649
IMI-T	VE	1, 14	10.90**	0.483	0.005
	SR	1.44, 20.11	1.37	0.089	0.269
	VE×SR	2, 28	1.92	0.121	0.165
IMI-E	VE	1, 14	25.34***	0.644	< 0.0001
	SR	2, 28	12.54***	0.472	< 0.0001
	VE×SR	1.23, 17.23	0.87	0.058	0.388

Significance codes: *p<0.1, **p<0.01, ***p<0.001.

Cybersickness. Table 2 lists the average total severity ratings with standard deviations of the SSQ data. A Wilcoxon signed-rank test revealed that the SSQ scores were significantly higher after all cases of the VR experiences: InvisibleBody under LowVisuals VE (p=0.003), Shoes under LowVisuals VE (p=0.005), HumanAvatar under LowVisuals VE (p=0.002), InvisibleBody under HighVisuals VE (p=0.014), Shoes under HighVisuals VE (p=0.005), and HumanAvatar under HighVisuals VE (p=0.006).

Table 2　Mean and SD values of cybersickness scores before and after each tested condition

Conditions	Before	After
LowVisuals & *InvisibleBody*	5.735±1.309	16.955±3.460
LowVisuals & *Shoes*	8.727±1.954	15.209±2.976
LowVisuals & *HumanAvatar*	4.987±1.920	11.719±2.124
HighVisuals & *InvisibleBody*	6.732±2.481	14.711±4.971
HighVisuals & *Shoes*	6.981±2.472	12.716±3.178
HighVisuals & *HumanAvatar*	7.231±2.015	12.467±3.002

5.3　Correlation report

To find possible correlations between physical performance data and subjective responses to questionnaires, Pearson product-moment correlation analysis was conducted. The results revealed a weak positive correlation between the preparation time for jumping and ownership (r=0.251, p=0.017). A weak positive correlation was found between the actual jumping distance and presence (r=0.281, p=0.007). There was also a weak positive correlation between the preparation time for jumping and UDT (r=0.263, p=0.012).

6　Discussion

Physical performance. Some significant differences were found among the tested conditions. When

jumping with HighVisuals, the average preparation time with HumanAvatar was higher than that with InvisibleBody or Shoes. From our observations, the participants usually took some time to look around in the environment and prepare before jumping. The actual jumping distance with InvisibleBody was significantly longer than those with Shoes (+0.061m) and HumanAvatar (+0.074m) in both LowVisuals and HighVisuals VEs. Compared with the target jumping distance (0.8m), the actual jumping distance with LowVisuals was significantly shorter (−0.139m), which could be evidence for the potential use of RDJ.

Detection thresholds for gains. Considering the effects of VE and SRs on the detection threshold for horizontal translation gains in RDJ, the user study results indicated that the LDTs varied from 0.362 to 0.692, PSEs varied from 0.898 to 0.972, and UDTs varied from 1.212 to 1.590. LDT with LowVisuals was significantly smaller than that with HighVisuals, whereas the UDT with LowVisuals was significantly larger than that with HighVisuals, regardless of which SR type was used. The results of our experiment were consistent with the open comments collected from the participants. Thirteen participants became more sensitive to the manipulations in jumping distances, and considered it easier to identify different manipulated jumping distances in a VE with HighVisuals than with LowVisuals because the former offered more visual cues to infer the jumping distance (texture of the ground, stones, trees, etc.). Similar to the findings of Kruse et al.[16], in the detected thresholds of RDW gains, our results confirmed that LDT with LowVisuals was significantly smaller than that with HighVisuals. Moreover, our results revealed a larger UDT value with LowVisuals than with HighVisuals, which was not established in previous research. This result suggests that a larger translation gain can be adopted without users noticing under the condition of VE with low visual cues, which is an important factor for designing new redirection VR projects. From the user study results, none of the detection thresholds were significantly different under SR conditions. This indicated that SR conditions have little impact on VR users' perceptions in RDJ, which means that VR designers do not have to spend much effort considering the effect of different SRs on redirection techniques. However, studying combined rotation and curvature manipulations in jumping with SR conditions is worthwhile to further validate this conclusion. The collected comments on how the SRs influenced the participants' choices in the pseudo-2 AFC task were also mixed. Four participants confirmed that HumanAvatar was the best because it was more natural to see their full body. Two participants commented that HumanAvatar and Shoes were at the same assistance level, both better than InvisibleBody, because they relied mainly on the virtual feet model to estimate the landing positions. For participants who leveraged the perceived speed of motion as the main cue for distance estimation, although the comments on the types of SRs were not significantly different, the HumanAvatar could introduce visual occlusion, and the shadow of the body might also have a side effect on their perception. Differing from previous findings in RDW where the threshold for the range of translation gains is smaller when the user can see his or her visual feet[16], our results in RDJ did not reveal such differences among SR types. The possible reason was that the walking and one-time two-legged takeoff jumping were two different action modes. Inferring translation gains might be easier with gait perception during walking[1] than with two-legged takeoff jumping.

Other subjective measures. According to the user study results, the presence scores with HighVisuals were significantly higher (+1.419) than those with LowVisuals for all SRs. Furthermore, the presence score with HumanAvatar was the highest among all SRs. The embodiment sense of HumanAvatar was significantly higher than that of Invisible Body (+2.527) and Shoes (+1.288). In addition, the embodiment was higher with HighVisuals than that with LowVisuals. The perceived tension during jumping was only significantly different in VE, where a lower visual richness had a higher tension value. The perceived enjoyment scores were significantly different between the two VEs and for different SRs. We observed

increased enjoyment when more visual cues were presented. These results suggested higher presence, enjoyment, and lower tension may be the reasons why it is more difficult for participants to notice jumping manipulation in a VE with high visual cues. Significant increases in cybersickness were perceived by participants for all the conditions.

Correlations were found between objective performance and subjective perception measures. First, a positive correlation was found between the preparation time and the embodiment ownership. Second, the actual jumping distance was positively correlated to the presence. Finally, a positive correlation was found between the UDT for gains and the preparation time for jumping. A sound explanation was that if a participant made a long preparation for a jump, he or she might expect a good jump performance with a longer jumping distance, leading to an increased UDT.

Open comments. Seven participants commented that larger gains made them feel relaxed whereas smaller gains made them feel resistant during jumping. Two participants remembered that when they jumped from the grid center in LowVisuals VE, the shadow of HumanAvatar was helpful for jumping distance inference by observing the relative position between the shadow and the frontal horizontal line. Nine participants complained about the HMD weight and its low air permeability, which affected the virtual experience. Nonetheless, it did not influence the distance perception.

Recommendations. From the results, we deduce design recommendations regarding VEs and SRs for RDJ locomotion in VR.

• R1. To make better use of the physical space, we suggest presenting fewer visual cues to make inferring distance manipulation difficult (e.g., the grid scene in our experiment).

• R2. Increasing the preparation time could be a method to increase the UDT in high-visual-richness VEs. One possible solution consists of presenting a full virtual body to users along with the evidence of a weak positive correlation between them and the virtual body.

• R3. Based on the actual jumping distance results, avoid using an invisible body representation in a high visual cue VE because this might lead to an actual jumping distance close to the expected one, thus, suppressing the effect of RDJ.

Limitations. We clarified that under epidemic prevention and control regulations, we only recruited 15 subjects to participate in our experiment, and did not specifically consider the effect of gender[27]. In addition, different durations of break time across participants may affect the measurement of heart rates. We acknowledge that although the pseudo-2AFC task was designed to reduce bias in participants' responses, it still induced bias. For example, although we randomly assigned the "Longer" and "Shorter" answers to the left or right controllers counter-balanced in random order, subjects tended to respond to "Longer" in the task. Inattention bias could occur as well, considering the long experiment with many trials.

7　Conclusions

In this paper, we have presented a 2 (VE: low and high visual richness) × 3 (SR: invisible, shoe, human-like avatar) user study to investigate the effects of VEs and SRs on physical performance and subjective perception in redirected forward jumping. While our findings in RDJ were partially consistent with existing RDW gain threshold estimation work regarding the influence of the visual richness in VE[16], we hardly found significant differences of gain thresholds among different SRs. These results revealed different mechanisms of how SR visualizations affect the distance perception between walking and one-time two-legged takeoff jumping. We have also discussed the correlations between the performance and perception data, and potential strategies to make more use of the physical space.

Future work could include exploring gains for vertical or rotational jumps, which were not investigated in our experiment. In addition, comparisons between the walking- and jumping-based redirection techniques could be worth investigating to determine differences in effect. Finally, it might be interesting to test more flexible locomotion actions (e.g., multiple jumps) than the one-time two-legged takeoff jump. This work likely requires robust jumping phase-detection algorithms.

Declaration of competing interest

We declare that we have no conflict of interest.

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