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Effects of Virtual Environments and Self-representations on Redirected Jumping

Yi-Jun Li[1] Miao Wang[1,2*] De-Rong Jin[1] Frank Steinicke[3] Shi-Min Hu[4] Qinping Zhao[1,2]

1 State Key Laboratory of Virtual Reality Technology and Systems, Beihang University, China
2 Peng Cheng Laboratory 3 Universität Hamburg 4 BNRist, Tsinghua University, Beijing

Abstract

We design 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 jumping (RDJ), under six different combinations of virtual environments (VEs) (low and high visual richness) and self-representations (SRs) (invisible, shoes, human-like). Results suggested that both VEs and SRs influence users' perception and performance in RDJ, and have to be taken into account when designing locomotion techniques.

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

1 Introduction

Recently, RDJ has become hot topics in VR locomotion. The redirected jumping technique was proposed by Hayashi et al. [1]. With user studies, they measured thresholds of unnoticeable gains for horizontal translation, vertical translation and rotation. Jung et al. [2] measured the perception of curvature gains in jumping by asking the user to jump in VE with five raised pedestals. The detection thresholds of RDJ have wider ranges than those of redirected walking (RDW) [4], which means an even smaller physical space would be enough if we apply RDJ techniques instead of RDW. According to Kruse et al.'s research [3], users heavily rely on the visual cues of the VE and the modeling of feet to perceive the manipulation of translation gains in RDW.

Since there was no previous research on whether VEs and SRs influence users when applying RDJ, we conducted a comprehensive user study that investigated the effects of VEs and SRs on the perception and physical performance of RDJ. Based on objective experimental data and subjective survey results, we confirmed that VEs and SRs can affect the performance and perception in RDJ.

2 Experiments

In this paper, we mainly focus 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. A jumping action can be divided into five phases including *standing*, *ready*, *ascending*, *descending* and *landing* according to previous RDJ work [1,2]. The scaling of virtual jumping distance was applied during the *ascending* and *descending* phases. In our experiment, all jumping trials were limited to one-time two-legged takeoff jumping. We made two main hypotheses:

- **H1:** The range of unnoticeable translation gains is smaller in the high visual richness VE than that in the 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.

*e-mail: miaow@buaa.edu.cn

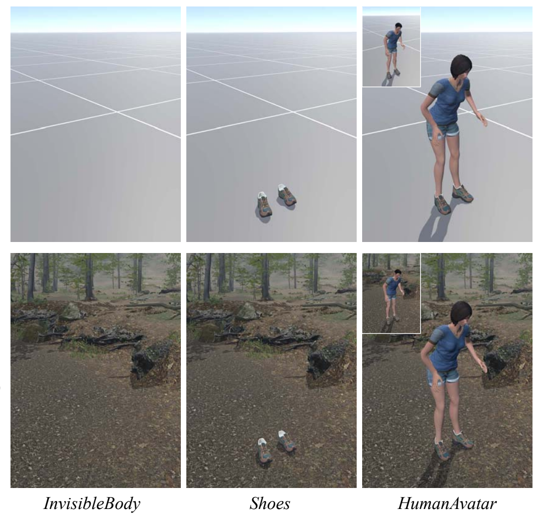

Figure 1: Illustration of combined VE and SR conditions in our experiment. **Top**: *LowVisuals*; **Bottom**: *HighVisuals*. **Columns from left to right**: *InvisibleBody*, *Shoes* and *HumanAvatar* (female and male).

We used a pseudo-two-alternative forced-choice (pseudo-2AFC) experimental design following previous RDW and RDJ studies [1, 3, 4]. Two VE conditions were tested, see Figure 1:

- **Low Visual Richness (*LowVisuals*):** a scene composed of a skybox and a plane on which $5m \times 5m$ regular grids were painted.
- **High Visual Richness (*HighVisuals*):** a scene of a forest with rich visual cues, such as trees, grass, and bridges.

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 pre-created male and female avatars.

We measured both objective physical performance and subjective perception of participants during the user study. The measured physical performance included preparation time during jumping, actual jumping distance, and heart rate intensity. Subjective perception measures were collected using questionnaires: 1) IGroup presence questionnaire (IPQ) for presence; 2) GFP embodiment questionnaire for embodiment; 3) Intrinsic Motivation Inventory questionnaire (IMI) for intrinsic motivation; 4) Simulator Sickness Questionnaire (SSQ) for cybersickness.

As shown in Figure 1, six conditions were tested with 9 discrete translation gains g_t controlled from 0.6 to 1.4 in 0.1 intervals and repeated 3 times in random order and participants were asked to horizontally jump 0.8 meters, which did not incur heavy physical loads. The gain variation range and jumping distance were also used by [1, 3]. 15 participants were recruited to complete the experiment. Each participant finished 6 trial blocks (2 VEs $\times$ 3 self-

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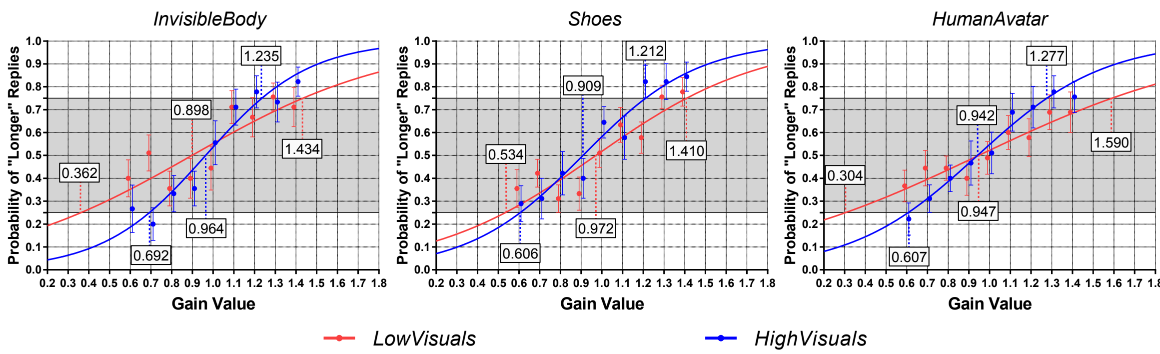

Figure 2: Plotted results of discrimination between virtual and physical distances for different conditions. The x-axis shows the applied translation gains and the y-axis shows the probability of the participants' perception that they jumped further than in the real world. For each gain value, the dots and bars indicate the mean values and the standard errors.

representations) with 27 trials (9 gains × 3 repetitions) in each block. Before each block, the participant was asked to complete pre-SSQ questionnaire, followed by three training trials with $g_t = 0.6, 1.0, 1.4$ known by the participant to help he/she understand how RDJ worked. After finishing all trials in one block, the participant filled in the post-SSQ, IMI, GFP and IPQ questionnaires on a PC. He/she then took a 5-minute break and started the next block.

3 Results and Discussions

Figure 2 shows the collected responses to translation gains and the fitted psychometric function curves under the tested conditions. The lower detection threshold (LDT), the point of subjective equality (PSE), and the upper detection threshold (UDT) are measured at the probability values of 25%, 50%, and 75% respectively. A two-way repeated measures ANOVA indicated that no significant interaction effect was found between VEs and SRs on detection thresholds. Pairwise analysis revealed that LDT in *LowVisuals* was significantly smaller than that in *HighVisuals* ($p = .041$), while UDT in *LowVisuals* was significantly larger than the one in *HighVisuals* ($p = .020$), which confirmed hypothesis **H1**. Nevertheless, no significant main effect of VE was found on PSE. No significant main effect of SRs was found on detection thresholds. Thus, **H2** was rejected. Different from previous findings in RDW where the detection threshold range is smaller when the user can see his/her visual feet [3], our results in RDJ did not reveal such differences.

Analysis of three questionnaires (IPQ, GFP, IMI) are shown in Table 1. According to the results, the presence, embodiment and enjoyment scores with *HighVisuals* was significantly higher than those with *LowVisuals*, and the presence and embodiment scores with *HumanAvatar* was the highest among all SRs. Moreover, the tension score was higher in *LowVisuals* than in *HighVisuals*. A Wilcoxon signed-rank test revealed that the SSQ scores were significantly higher after the experiments in all 6 conditions ($p < .02$).

Some significant differences of objective measurements were found among the tested conditions. When jumping with *HighVisuals*, the average preparation time with *HumanAvatar* was higher than that with *InvisibleBody* ($p = .023$) or *Shoes* ($p = .008$). From our observation, participants usually took some time to look around in the environment and get ready before jumping. The actual jumping distance with *InvisibleBody* was significantly longer than those with *Shoes* ($p = .028$) and *HumanAvatar* ($p = .007$) in both *LowVisuals* and *HighVisuals* VEs. No significant interaction effect was found in heart rate intensity between VEs and SRs, and no significant main effect of VEs or SRs was found, either.

4 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

Table 1: Analysis of IPQ, GFP, IMI Tension (IMI-T) and Enjoyment (IMI-E) with two-way repeated measures ANOVAs. (significance codes: $^{**}p < 0.01$, $^{***}p < 0.001$)

Measure	Effect	df	F	η^2	p
IPQ	VE	1, 14	28.92***	.674	<.0001
	SR	2, 28	8.79**	.386	.001
	VE×SR	1.32, 18.43	1.31	.085	.28
GFP	VE	1, 14	18.65***	.57	<.001
	SR	1.27, 17.75	26.34***	.653	<.0001
	VE×SR	1.34, 18.81	.31	.022	.649
IMI-T	VE	1, 14	10.90**	.483	.005
	SR	1.44, 20.11	1.37	.089	.269
	VE×SR	2, 28	1.92	.121	.165
IMI-E	VE	1, 14	25.34***	.644	<.0001
	SR	2, 28	12.54***	.472	<.0001
	VE×SR	1.23, 17.23	.87	.058	.388

and subjective perception of 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 [3], we hardly found significant differences of gain thresholds among different SRs. Such results revealed different mechanisms of how SR visualizations affect the distance perception between one-time two-legged takeoff jumping and walking.

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