Redirected Jumping: Perceptual Detection Rates for Curvature Gains

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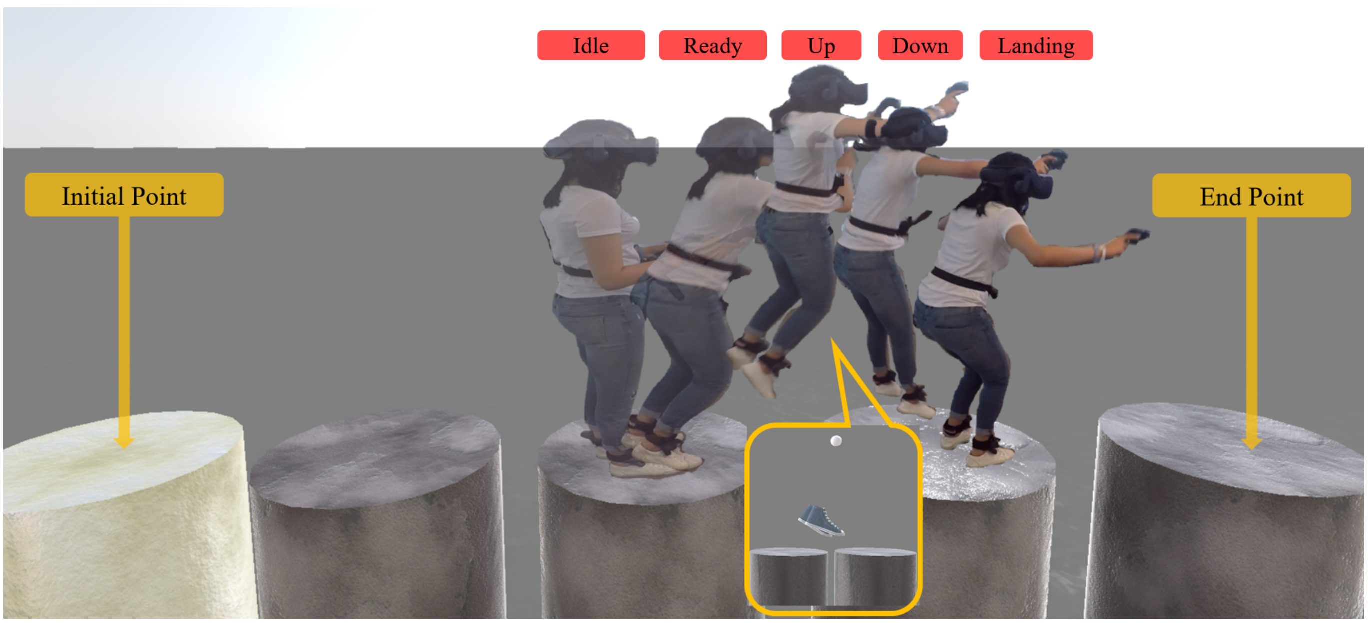

Figure 1. Jumping in a virtual environment: Experiment participants were asked to jump along a virtually-straight sequence of five round platforms. A single jump typically consists of five phases from idle to landing. During the jumps, participants were redirected with four gain magnitudes under investigation, and asked to identify if their overall motion bent to the left or right. Two virtual shoes and a sphere were rendered to show foot and waist positions.

ABSTRACT

Redirected walking (RDW) techniques provide a way to explore a virtual space that is larger than the available physical space by imperceptibly manipulating the virtual world view or motions. These manipulations may introduce conflicts between real and virtual cues (e.g., visual-vestibular conflicts), which can be disturbing when detectable by users. The empirically established detection thresholds of rotation manipulation for RDW still require a large physical tracking space and are therefore impractical for general-purpose Virtual Reality (VR) applications. We investigate Redirected Jumping (RDJ) as a new locomotion metaphor for redirection to partially address

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this limitation, and because jumping is a common interaction for environments like games.

We investigated the detection rates for different curvature gains during RDJ. The probability of users detecting RDJ appears substantially lower than that of RDW, meaning designers can get away with greater manipulations with RDJ than with RDW. We postulate that the substantial vertical (up/down) movement present when jumping introduces increased vestibular noise compared to normal walking, thereby supporting greater rotational manipulations. Our study suggests that the potential combination of metaphors (e.g., walking and jumping) could further reduce the required physical space for locomotion in VR. We also summarize some differences in user jumping approaches and provide motion sickness measures in our study.

Author Keywords
Redirected Jumping; Virtual Reality; Psychomotor Performance; Sensory Thresholds; User-Computer Interface; Walking

CCS Concepts
•Human-centered computing → **HCI design and evaluation methods; User studies; Mixed / augmented reality; Virtual reality; •Computing methodologies** → *Perception;*
https://dl.acm.org/ccs/ccs_flat.cfm

INTRODUCTION

Travel through virtual reality (VR) environments is a fundamental requirement for many immersive VR experiences. Considering that VR worlds can be much larger than the user's physically navigable space or tracked area, several locomotion metaphors have been suggested for handling arbitrarily large virtual spaces, with redirected walking, walking in place, joystick-based locomotion, and teleportation [6, 19, 20, 23] among the most common. Because real walking provides the most natural method for locomotion in VR, researchers investigated the effects of *Redirected Walking* (RDW) techniques that manipulate the user's orientation by injecting rotation during walking, resulting in a curvature gain, i.e., a difference between the user's physical rotation along the path and the virtual-path curvature. To estimate the physical space needed for infinite virtual walking, studies of RDW have estimated the maximum possible gain without the effect being substantially detectable. For example, Steinicke et al. [20] reported that subjects could be shifted by 13° per 5m of walking, theoretically allowing the user to walk infinitely along a circular arc of radius of at least 22m. Because RDW quality is a subjective matter, Rietzler et al. [18] revisited the technique in terms of cognitively acceptable levels with higher gains, and they reported that up to a 20°/m curvature gain was acceptable. However, they argued that the gain cannot be used constantly for a long VR experience because of discomfort.

As a redirection technique for smaller tracking areas and to allow larger locomotion freedom in VR, Hayashi et al. [9] proposed *jumping* as a new locomotion metaphor because 1) jumping is also a natural behavior in daily life, and 2) it produces a significant amount of vestibular noise, which can be used for more redirection compared to normal walking. They found significant effect with jumping in a VR environment consisting of a floor grid and small spheres representing tracked body parts. This previous work on *Redirected Jumping* (RDJ) only considered a single jump, and manipulated gains with regard to distance, height, and rotation. Therefore, the effects of more-continuous jumping motions, as well as the possibilities for curvature gain, are still unexplored. To investigate the effects of multiple jumps along an arc, here we study the perceptual detection rates for various curvature gain levels in VR.

To compare with prior RDW research as directly as possible, we followed a similar experimental method to prior work on conventional RDW. Our experiment had subjects jump along a series of five raised pedestals several times using four curvature gains. Subjects were asked to indicate, per path, if they were redirected to the left or right. Most notably, we found that detection rates from RDJ were substantially lower than prior RDW results, meaning subjects were less able to correctly guess the direction of the curvature for RDJ than with RDW under similar gain conditions. Our results show a curvature gain that is below threshold even at three times the threshold value reported for RDW, suggesting the RDJ threshold is even more than three times higher. We also consider simulator sickness questionnaire results, which are reasonable for a physical locomotion technique.

RELATED WORK

Travel is a fundamental interaction in VR [4]. Moving through VR environments with real physical walking can provide a more natural interface than other travel methods, such as controller-based flying or walking-in-place [22]. However, the applicability of real walking is limited due to space constraints including limited room size, limited motion tracker range, and the use of tethered headsets. Various redirection approaches have been proposed that allow limited-space real walking to produce larger-space virtual motion. Basic approaches include scaling user translation [24], scaling user rotation, or injecting rotation proportional to translation rate (linear velocity) [17]. Surveys of redirection techniques have classified these examples as subtle [14] [21], in contrast to overt techniques such as teleportation and explicit requests for the user to reorient.

An ideal realization of subtle techniques makes them imperceptible to users, which also suggests that they avoid effects on cognitive performance or simulator sickness. This has led to multiple studies to identify manipulation levels below which redirection is imperceptible, or only detectable at a desired threshold rate, using psychophysical threshold detection methods [7]. For example, Steinicke et al. [20] estimated gain thresholds for the three subtle techniques mentioned above. Besides imperceptibility, researchers have studied cognitive effects such as memory demands of redirection and of other travel approaches [5] [13]. Other work has investigated visual distractors to mask redirection [16], the reinforcing effects of spatialized sound [15], and exploiting eye saccades and blinks as intervals for redirection [3].

METHODS

We conducted an experiment to investigate the perceptual detection rate for participants jumping between platforms along a virtual pathway. We collected and analyzed data for varied curvature gain (Gc) between a virtually-straight path and a physically-redirected path of jumping along a circular arc of radius r. Gain is defined in relation to radius, using a standard definition, as $\text{Gc}=\frac{1}{r}$.

Experimental Platform

Study Design

To elicit a natural jumping behavior, the VR environment consisted of target platforms for jumping (see Figure 1), resembling endless running games like Temple Run or platformers like Super Mario Bros. We gathered detection rates based on the method of constant stimuli with a *two-alternative forced-choice* (2AFC) response procedure. Per trial, subjects jumped for about 3m total and were asked to detect curvature gain direction (left or right) for the trial having one of four gain levels. Four jumps per trial were required to move from the initial platform to the end platform. Requiring users to choose left or right results in a 50 percent natural response rate, i.e., answers are expected to be correct 50 percent of the time, on average, when subjects cannot detect redirection at all. In contrast to approaches allowing subjects to answer that they detect no effect, the 2AFC approach avoids a type of response bias in which unconfident subjects could too often report no effect [7]. However, there are other remaining biases, such as inattention or a bias towards one response over another (relevant when considering left and right response rates separately rather than pooling into a rate of correct response). A similar 2AFC approach was used in other redirection studies, including the one we compare to directly [20].

We modeled virtual sneakers and a sphere (waist) to represent the participant's abstracted jumping behavior and position. The platforms were five vertical cylinders of 35cm radius and of equal height, with uniform inter-platform spacing of 7cm (edge-to-edge). Platforms appeared in the middle of a sea with ambient sea sounds playing throughout, and a gentle sea wave rendered to provide some modest optical flow, though the impact was not a focus in this study. To discourage fast continuous jumping, platforms were added one-by-one such that the next target platform (the platform following the current landing target) appeared during jumping. To observe a desired jumping style, we asked the subject to use a high vertical jump rather than a long horizontal jump.

We chose to test injected rotation angles (defined shortly) based on a RDW paper [20]. That work tested totals of {5°, 10°, 15°, 20°, 30°} for 5m of walking, corresponding to curvature radii of {57.3, 28.65, 19.10, 14.32 and 9.55} meters, respectively, and found a detected threshold curvature gain of ±0.045, or 13° per 5m walking. Based on this information, and considering an expected higher vestibular noise for jumping than for walking, we decided to use higher redirection angles of {7.5°, 12.5°, 17.5°, 22.5°} per total 3m jumping distance. Because of our desire to limit the number of jumps in our study to prevent physical fatigue, we decided to use four angles and a shorter distance instead of five angles and 5m. We coded the selected angles to $\{\pm \textit{Very Low}, \pm \textit{Low}, \pm \textit{Middle}, \pm \textit{High}\}$ in this study, corresponding to curvature radii of approximately {23.01, 13.8, 9.82, 7.63} meters, respectively. Therefore, the curvature gains that we used in this study were $Gc = \{0.04, 0.07, 0.1, 0.13\}$ and we expected these gains would cover a wide enough range compared to the gain (±0.045) in the previous work.

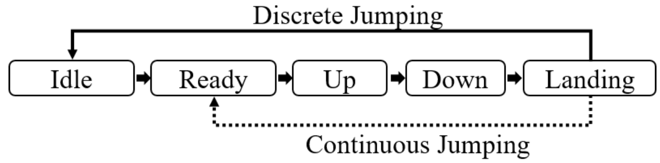

Figure 2. Jumping Phases

Jumping Recognition

Jumping is a complicated behavior that can be categorized into several types depending on the direction (e.g., vertical or broad), body dynamics (e.g., running or standing), and other considerations such as footstep type and arm swing [12, 2]. In this research, to reduce a confounding variation in jumping type, we verbally asked the participants to perform more-vertical jumps than just broad jumps from a standing position. Also, we expected that the vertical jump could maximize the vestibular noise while reducing the safety issues in our limited space. We did not limit other types of jumping behavior (e.g., arm swing, foot stepping, jumping using both feet or a single foot, or unexpected jumping styles).

Jump Phases

Based on prior biomechanics research [12, 2], we divided the jumping cycle into five phases called Idle, Ready, Up, Down, and Landing, for our phase recognition approach:

- **Idle**: The user is initially standing upright and is stationary. A transition from this phase to Ready occurs when the hips and head are lowered.
- **Ready**: The user exhibits downward movement by flexing the knees and hips. A transition to the Up phase occurs based on a combination of high positions of the head, hips, and feet.
- **Up**: The user extends the knees and hips to jump up off the ground, and reaches the highest point in the air. A transition to the Down phase occurs when hip movement direction is downward.
- **Down**: The user slightly bends the knees and hips, approaching Landing. A transition to the Landing phase occurs based on the positions of the head, hips, and feet (no longer high).
- **Landing**: The user flexes to take the shock of the landing and hold balance. A transition to Idle occurs when hip motion has stabilized and the head and hips are no longer low.

Based on the definition of each phase, we tracked the participant's motion (head, waist, and foot), categorized the motion into a jumping phase, and injected predefined per-phase gains.

Depending on the phase-iteration time and the time spent idle, jumping can be defined as either a continuous or discrete movement (see Figure 2). To summarize subject behaviors, if a subject was *Idle* after *Landing* and stayed on a platform for over one second, we classified the jumping as discrete, and otherwise classified it as continuous. We allowed subjects to jump using either both feet simultaneously or one foot in front. Based on recorded video, we report the dominant jumping behavior of 15 subjects in Table 1 (recordings from two participants were lost).

Injecting Gain

We describe *curvature gain* as the resulting effect that the user's motion follows an arc, while *injected rotation* is what causes the gain and how the implementation works. Each of the five jumping phases described above could include noise in the user's own sense of orientation, and more noise would be expected upon landing while the falling body stabilizes. We injected a virtual user rotation proportionally for each phase of the jump to induce the corresponding desired overall curvature gain. We used predefined coefficients per phase to distribute injected rotation between four phases (*Idle*=0.003, *Up* and *Down*=0.07, *Landing*=0.012), with no injected rotation during *Ready*. We selected these coefficients through an empirical formative study before we ran the reported experiment, and we found that most participants would stabilize their orientation or had slight natural body movement even in the idle state in practice. Considering that this mismatched our definition somewhat, we applied only a negligible rotation gain (e.g., 0.003) in this phase. Note that this injected rotation was relatively high in the phases of the jump where the subject had low visual awareness of the environment (*Up*, *Down*, and *Landing*), and relatively low when the user could concentrate on the environment's appearance (e.g., no rotation in the *Ready* phase). Note that we did not decide the coefficients proportionally, thus the total does not sum to 1.

Similarly, a higher jumping *velocity* (ω, in *rad/sec*) would likely make the subject less aware of redirection, so we incorporated a velocity-dependent rotation effect that changed per jump and per subject according to Equation 1, where α is a per-phase coefficient.

$$\textit{Injected Gain} = \alpha * \omega \tag{1}$$

Thus, in this experiment, a maximum redirection per jump was not fixed. But, the minimum redirection was set based on pre-calculated theoretical rotation considering the number of jumps, total desired redirection, and phase time estimates. Rotation was injected per jumping phase, and we divided the redirection in each phase of the jump into "steps". We then calculated the amount to rotate at each step from the known parameters, and otherwise proportional to the jumping velocity, until the desired overall redirection amount was reached. If the achieved rotation was equal to or over the pre-calculated theoretical rotation, then no further redirection was applied. In other words, until the total redirection met the targeted angle for each jump, redirection was injected.

Table 1. Dominant jumping type used by participants. We did not restrict the types of jumping behavior (e.g., arm swing or foot stepping) as long as the user performed a vertical jump to maximize vestibular noise while reducing the safety issue from the broad jump. (NOTE: jumping type data from two participants was lost and is therefore not shown in the table due to a recording problem)

#	Continuity	Step	Arm
1	Discrete	Both	No
2	Discrete	Both	Yes
3	Continuous	Both	No
4	Discrete	Single	No
5	Continuous	Both	No
6	Discrete	Both	Yes
7	Continuous	Single	No
8	Continuous	Both	No
9	Continuous	Both	Yes
10	Continuous	Both	Yes
13	Continuous	Both	No
14	Continuous	Both	Yes
15	Discrete	Both	No

Procedure

The experimental procedure was approved by the human ethics committee of the university. Before the experiment, subjects who passed a medical checklist filled out an informed consent form and received detailed instructions about the experiment. This was followed by a demographic questionnaire and a pre-SSQ (simulator sickness questionnaire). We attached VR devices to the subject as shown in Figure 3. We provided a training session to the participants about the jumping procedure and manipulation of the controllers for the direction answer. During the training session, the subject and experimenter had verbal communication to confirm if they understood the task in the experiment. We randomized the curvature gain and the direction for the training session, and the subject had a trial under the supervision of two staff members to monitor and minimize possible physical risks during the trial (discussed in the Conclusion). At the initial platform, the participants confirmed when they were ready to jump by pressing the right Vive controller trigger. When reaching the last platform, an in-game questionnaire appeared at eye level, asking the subject to respond with a direction as follows: "In which direction has the path been bent? Touch the LEFT pad for LEFT, Touch the RIGHT pad for RIGHT".

Once the subject completed a trial, the virtual platforms vanished and the experimenter guided the subject back to the initial platform for the next trial. To protect the subject from fatigue and physical injury that could result from jumping, we limited the total number of jumps and the distance between platforms, and subjects were instructed to stop or pause if needed at any time during the experiment. No subject asked for a break in the experiment. Subjects each performed 64 total jumps: four trials per each of four conditions (angle), with four jumps per trial. After completing all the trials, the subject exited the VR system and filled out a post-SSQ questionnaire. The average time to complete all jumping trials including the training session was eight minutes and 30 seconds.

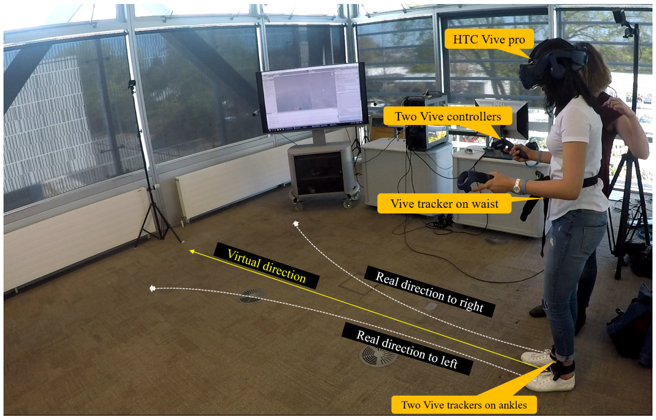

Figure 3. Experiment setup and Redirected Jumping scenario: An HMD, two controllers, and three trackers were used. In the physical space, the subject curved to the left or right (white dotted curves), while the virtual jumping appeared straight in VR (yellow solid line).

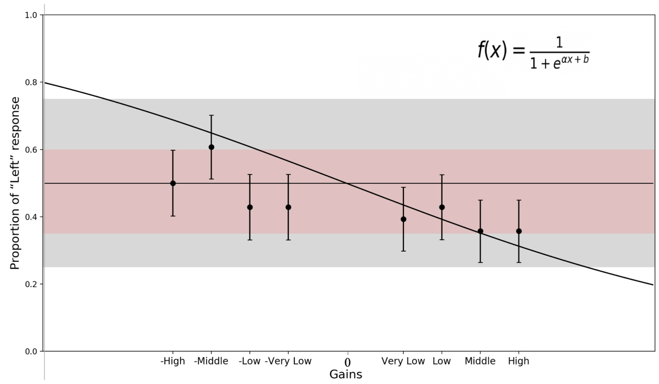

Figure 4. Probability, based on pooled data, of the user answering left for each curvature gain level (signed). Random guessing would result in probability 0.5. The left half of the graph corresponds to actual left-bent paths, and the right half to right-bent paths. The gray region corresponds to response rates with below 50% correct detection (which includes adjustment for guesses). The red region shows the range of observed means.

Participants
Eight male and seven female subjects participated. Ages ranged from 18 to 41 ($M = 26.6$, $SD = 6.6$). Subjects were screened using a medical checklist for susceptibility to physical fatigue, considering the extent of jumping during the study. We confirmed that all participants had normal or corrected vision before participation. Most subjects were students or members of a department of engineering. Only one subject reported more than minimal prior VR experience. Participants received a compensation voucher for their time.

Hardware Setup
We performed the experiment in a 4m by 4m room using an HTC Vive Pro headset with two Vive controllers and three additional Vive trackers. The additional trackers were attached to the ankles and waist to recognize the jumping phases and to display position and orientation information. We ran the software on an Intel Core i7 CPU, an NVIDIA GeForce GTX 1080 Ti GPU, and 16GB RAM. We used the Unity5 game engine to render the VR environment, log the data, and for system control. Our experiment system maintained a frame rate of at least 60 frames per second. A 55-inch TV was placed nearby to monitor the virtual environment while protecting the participant from any harm (see Figure 3).

RESULTS
This section presents the redirection detection rates and the SSQ scores resulting from the experiment.

Curvature Gain
The result of the 2AFC task is illustrated in Figure 4. During the experiment, the number of 'Left' responses was recorded per condition (angle) and subject, with a no-detection rate of 0.5 (natural response rate, middle line in Figure 4). The overall proportion of 'Left' responses, pooled across subjects, was computed per condition. We plotted the mean probability for the response that the physical path was curved to the left against the curvature gains at the level of 25%-75% probability range (gray color area). Surprisingly, subjects responded in an even smaller probability range between about 35%-60% (red color area) for all curvature gains. It is standard, in redirected locomotion studies, to fit response rates to a bipolar sigmoid function that models detection rates for estimating detection thresholds. However, the results, staying well below threshold, did not cover a range for clear fitting to the psychometric function of the form

$$f(x) = \frac{1}{1+e^{ax+b}}$$

, with the real values a and b. Nonetheless, importantly, we do observe the expected trend of increasing correct detection with higher gain magnitude, and the results place all our gains well below the detection threshold.

To give a direct comparison between RDJ and RDW, we adopted the per-meter notation from Rietzler et al.[18], who reported that 2.6°/m and 4.9°/m were the maximum curvature gains from Steinicke et al.[20] and Grechkin et al.[8], respectively. In our result, we suggest that RDJ in VR could induce a much higher detection threshold, above our highest gain of 7.5°/m (about 2.9 times the threshold reported by Steinicke et al., and 1.6 times Grechkin et al.). Given that response rates were well within the threshold range of 50% correct detection, even much higher detection thresholds are likely for RDJ.

SSQ
Because jumping could become physically exhausting or uncomfortable compared to walking, we measured simulator sickness by means of Kennedy's Simulator Sickness Questionnaire (SSQ), which asks the participant to score 16 symptoms with scores from 0 (none) to 3 (severe) [10, 1]. These are further categorized into three groups: Oculomotor, Disorientation, and Nausea, which have maximum possible scale scores as given in the table caption (Table 2).

The Pre-SSQ score average over all subjects was 19.95 and the Post-SSQ score was 29.17. Such SSQ increases are typical compared to prior reported values, e.g., pre-SSQ was 11.45 and post-SSQ was 32.49 in a recent RDW study exploiting eye blinks [11]. We report the detailed SSQ scores in Table 2.

Table 2. SSQ result. The maximum possible scores are 200 for nausea, 159 oculomotor, 292 disorientation, and 235 scaled total.

	Nausea	Oculomotor	Disorientation	Total
Pre	12.72	20.21	18.56	19.95
Post	27.98	21.73	27.84	29.17

An interesting finding is that the *Disorientation* section shows the biggest difference between the pre- and post-SSQ scores. Further, we investigated a single item of the questionnaire to better understand some related aspects such as physical fatigue, despite the fact that the SSQ was not originally designed to measure that. In particular we found that the *Sweating* score rose noticeably from 0.27 pre-SSQ to 1.33 post-SSQ.

DISCUSSION

The aim of this study was to explore the potential of RDJ in general, and for enhancing curvature gains in particular, hence allowing participants to explore large virtual environments in a confined physical space. From the results, it seems that participants were not able to differentiate the direction of injected rotation. If this was because they were not able to detect that there was an injected rotation at all or because they were not able to detect the direction of the injected rotation can be deduced from the results.

In our observation of participant behavior during the trials, we noted that they adjusted their orientation after jumping. However, they seemed to do this unconsciously and were unaware that rotation had been injected artificially. They appeared to have perceived the changed direction as being caused by the jump. We infer that high vestibular noise was induced while jumping, and the difference of disorientation before and after jumps supports this. Since jumping is not a precise movement, we conjecture that subjects corrected themselves thinking they had jumped imprecisely, not because they had been redirected. The relatively low scores in the SSQ suggest that neither the selected Virtual Environment nor the jumping itself induced much simulator sickness. Hence, it does not contraindicate the use of a physical jumping metaphor for redirection or as a game element.

Although we have tested a variety of curvature gain parameters, this study provides only a first indicator of the potential of RDJ as a supportive locomotion metaphor. When comparing our study with other work on RDW such as the studies from Steinicke et al. [20] we also need to take into consideration that their work on RDW was carried out using the 3DVisor Z800, an HMD with a resolution of 800x600 @ 60Hz and a 40 degree diagonal field of view. We used a current HTC Vive Pro with much better specifications. We also added virtual representations of the feet of the participants as well as a sphere to indicate the center of the body.

The findings from this study are very encouraging. In the future, we will need to explore what effect the use of current equipment has on the potential of curvature gains in VR. In addition, we need to explore in more depth other possible contributing factors to the high apparent threshold. For example, an elevated threshold can suggest seamless integration of the exaggerated rotation in the mental model of the participants who therefore did not consciously detect it, or it could be due to some type of general confusion of participants, or influenced by various factors of the environment type or jumping style. Finally, future studies can include substantially higher gain values to support a more complete understanding of detection rates and to allow precise threshold estimation.

Implications

Several RDJ variations could be beneficial in practice. For example, multiple jumps could be useful for redirection of height (i.e., jumping up or down to a virtual step). RDJ could give a varying sense of height which gives a more dynamic option for VR designers. Also, jumping could be very attractive for gaming scenarios or in fitness applications, although with elevated expected fatigue and related safety concerns. Some games with induced physical fatigue (e.g., Wii sports) have been successful in the commercial market, and have potential, as long as they have a strong fun factor.

Limitations

The major limitation of jumping is that it creates safety concerns, such as collisions with objects or walls, or increased fatigue, leading to further problems. Similar to RDW, in order to prevent such problems, RDJ requires adequate empty space. As a contribution in this paper, the space required for RDJ is substantially less than for RDW. Therefore, if RDW and RDJ are combined, designers should be able to reduce the necessary space requirements for VR experiences even further. Another suggestion to reduce the negative safety effects of RDJ is to implement a redirected jumping in place (RDJIP) approach, instead of RDJ, but this will require additional study. In terms of fatigue, short-hopping could reduce body fatigue, or even just a jumping gesture (crouch and then stand) could work (the Nintendo Wii supports this with the Wii Fit Balance Board). This limited amount of movement could also reduce the effectiveness of the redirection. In both of these cases, head movement (and therefore noise) is reduced, which would probably reduce the amount of gain we can achieve.

CONCLUSIONS

A main goal of this paper was to introduce RDJ as a supportive locomotion metaphor for integration with other locomotion techniques, not necessarily as a main locomotion method. In this research, we showed a potential for RDJ to address some of the space limitation of standard RDW in VR. We explored the perceptual detection rates on curvature gains using a psychophysics study. In our experiment, RDJ allowed the application of about three times higher curvature gain compared to the reported values for RDW. We believe RDJ can be applied with rotation and translation, and has the possibility of using relatively small jumps if high gains are tolerated. Therefore, we suggest that combining RDJ with locomotion techniques such as RDW or WIP could create more effective redirection techniques for navigating virtual environments in very confined physical spaces.

Before deployment of jumping-based VR travel, its safety must be carefully considered. Consumer VR users typically do not have assistants monitoring their behavior, and they may want to be immersed for much longer than our study participants. Common risks of real walking in VR are exacerbated with jumping, and these risks include colliding with physical objects, being pulled or tripped by device tethers, and reduced balance if visual rendering mismatches vestibular cues. As a starting point for safety, devices should be wireless and lightweight and visual feedback must give clear indicators before physical obstacles are reached. Using small (real) jumps may improve safety and comfort, but possible disorienting side effects of redirection gains for small jumps should be assessed.

In the future, we will explore an integrated locomotion technique with RDJ and RDW. For example, the subject will walk on a virtual pathway and jump to avoid virtual obstacles while we inject curvature gains proportionally depending on the locomotion type. To investigate the effect of the combined locomotion technique, we will conduct a usability test in terms of detection thresholds, applicability in VR, and user preference.

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