Cognitive Resource Demands of Redirected Walking

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Abstract—Redirected walking allows users to walk through a large-scale immersive virtual environment (IVE) while physically remaining in a reasonably small workspace. Therefore, manipulations are applied to virtual camera motions so that the user’s self-motion in the virtual world differs from movements in the real world. Previous work found that the human perceptual system tolerates a certain amount of inconsistency between proprioceptive, vestibular and visual sensation in IVEs, and even compensates for slight discrepancies with recalibrated motor commands. Experiments showed that users are not able to detect an inconsistency if their physical path is bent with a radius of at least 22 meters during virtual straightforward movements. If redirected walking is applied in a smaller workspace, manipulations become noticeable, but users are still able to move through a potentially infinitely large virtual world by walking. For this semi-natural form of locomotion, the question arises if such manipulations impose cognitive demands on the user, which may compete with other tasks in IVEs for finite cognitive resources. In this article we present an experiment in which we analyze the mutual influence between redirected walking and verbal as well as spatial working memory tasks using a dual-tasking method. The results show an influence of redirected walking on verbal as well as spatial working memory tasks, and we also found an effect of cognitive tasks on walking behavior. We discuss the implications and provide guidelines for using redirected walking in virtual reality laboratories.

Index Terms—Redirected walking, cognitive demands, locomotion, virtual environments

1 INTRODUCTION

Virtual reality (VR) technologies are often used in application domains which involve simultaneous spatial tasks and goals competing for the limited cognitive resources of users. In particular, simultaneous navigation, locomotion and interaction with objects in virtual environments (VEs) are essential tasks for many three-dimensional (3D) applications, such as urban planning, training, or entertainment [33].

Locomotion in Virtual Environments

Traditionally, immersive virtual environments (IVEs) were restricted to visual displays combined with interaction devices, e.g., joystick or wand, for virtual position control. Recently, traveling through IVEs by means of intuitive, multimodal methods of generating self-motion is becoming increasingly important to improve the naturalness of VR-based interaction. In particular, traveling by means of real walking has received much attention recently due to results of perceptual and cognitive experiments showing that walking has significant advantages over other forms of traveling in terms of the user’s sense of feeling present in the VE [35], navigational search tasks [27], cognitive map buildup [28], and required cognitive resources [18].

However, while humans navigate with ease by walking in the real world, realistic simulation of natural locomotion is difficult to achieve in IVEs [33]. During walking in the real world, vestibular, proprioceptive, and efferent copy signals, as well as visual information create consistent multi-sensory cues which indicate one’s own motion, i.e., acceleration, speed and direction of travel. Real walking can be implemented in IVEs by mapping a user’s tracked head movements to changes of the camera in the virtual world, e.g., by means of a one-to-one mapping. Then, a one meter movement in the real world is mapped to a one meter movement of the virtual camera in the corresponding direction in the VE. While this implementation provides near-natural sensory feedback similar to the real world, it has the drawback that the user’s movements are restricted by the limited range of the tracking sensors and limitations of the workspace in the real world. The size of the virtual world often differs from the size of the tracked workspace so that a straightforward implementation of omni-directional, unlimited walking is not possible. Various prototypes of locomotion devices have been developed to prevent a displacement during walking in the real world. These devices include omni-directional treadmills [7, 30], motion foot pads, robot tiles [12, 13], and motion carpets [29]. Although these locomotion devices represent enormous technological achievements, they are still cost-prohibitive and will not be generally accessible in the foreseeable future.

Redirected Walking

Cognition and perception research suggest that cost-efficient as well as natural alternatives exist. It is known from perceptive psychology that vision often dominates proprioception and vestibular sensation when the senses disagree [5, 9]. In perceptual experiments, where human participants can use only vision to judge their motion through a virtual scene, they can successfully estimate their momentary direction of locomotion, but are worse in perceiving their paths of travel [6, 16]. Since humans tend to unwittingly compensate for small inconsistencies during walking, it becomes possible to guide users in IVEs along paths in the virtual world which differ from the paths perceived in the virtual world. This redirected walking enables users to explore a virtual world that is considerably larger than the tracked workspace [25]. Some techniques guide users on bent physical paths for which lengths as well as active turning angles of the visually perceived paths are maintained. However, if the physical paths are bent with a radius of less than 22 meters a user may observe the discrepancy between both worlds [31] and has to consciously follow the visual stimuli [11, 22], which may introduce severe cognitive demands.

Theoretical Models of Cognitive Resources

Human working memory draws from finite cognitive resources, for which several theoretical models have been proposed [10], which usually distinguish at least between verbal and spatial resources [2]. A model of cognition and working memory was proposed by Baddeley and Hitch [1, 2], which considers manipulation and storage of visual and spatial information in a speech-based loop. According to this model, access to verbal and spatial working memory and general attention is handled by a central executive. General attention is characterized by similar demands on verbal and spatial working memory.
Because of limitations in the sensory feedback and required control actions described above, redirected walking cannot be considered truly natural. The user is required to actively (consciously or subconsciously) compensate for the introduced manipulations. These aspects may cause users to employ strategies requiring additional cognitive resources, which compete for resources from the same pools that are utilized for successful completion of a user’s primary tasks.

In this article we analyze interactions between redirected walking and cognitive spatial and verbal working memory tasks. In particular, in this article we analyze and discuss:

- Effects of redirected walking on verbal and spatial working memory tasks.
- Influence of verbal and spatial tasks on locomotion behavior when using redirection.
- Implications for using redirected walking in IVEs.

The article is structured as follows. Section 2 discusses related work in the scope of the article. Section 3 details the experiment in which we evaluate cognitive demands during redirected walking. The results are presented in Section 4 and discussed in Section 5. Section 6 concludes the article and gives an overview of future work.

2 Related Work

Redirected walking in IVEs is currently the focus of many research groups, analyzing locomotion and perception in both the real world and virtual worlds [34]. Basic redirection techniques make use of a \textit{stop-and-go} approach, i.e., the virtual world is rotated around the center of stationary users until they are oriented in such a way that no physical obstacles are in front of them [15, 24, 25]. Then, users can continue to walk in the desired virtual direction. The alternative is to continuously apply redirection while the user is walking through the VE [11, 25, 32]. For instance, if users are walking straight ahead in the virtual world, small iterative rotations of the camera redirect them to walk along a circular path in the opposite direction in the real world.

When redirecting a user, the visual feedback is consistent with movement in the VE, whereas proprioceptive feedback reflects movement in the physical world. When the applied manipulations are small enough, the user has the impression of being able to walk in any direction in the VE without restrictions imposed by the limited physical workspace.

Steinicke et al. [31] have performed different experiments to identify thresholds which indicate just-noticeable differences between vision and proprioception while the user is moving. In particular, they determined thresholds for detecting translational, rotational, and curvature manipulations, which were formalized using locomotion gains [31]. Such gains describe ratios between a user’s path in the real world which is decoupled from their path in the VE. In order to determine detection thresholds for path curvature, users walked a straight path in the VE, which was bent by a curvature gain either to the left or to the right in the real world. Users had to judge if the physical path was bent left or right in a \textit{two-alternative forced-choice} (2AFC) task. According to Steinicke et al. [31], a straight path in the VE can be turned into a circular arc in the real world with a radius of at least 22m, for which users are not able to consciously detect manipulations. Thus, if the physical workspace in the VR laboratory supports a walking area of at least 45m×45m users can walk an infinite straight distance in the virtual world, while, in fact, they are walking a circular path in the real world. Although these psychophysical experiments revealed detection thresholds which provide insight into the ability of users to perceive redirected walking manipulations, no previous work has been performed to analyze which effect it has on cognitive resources when users are redirected. In particular, to our knowledge, no previous work provided insight into the amount of cognitive demands that are induced by redirected walking manipulations of different magnitudes on the walking user.

To answer these research questions, dual-task studies can be used, which are a widely used method to understand influences of cognitive tasks on traveling or locomotion gait and balance (see [38] for a review). The dual-task method requires users to perform a secondary task while performing a primary task to determine the costs involved in performing the concurrent task [4], such as performing an additional cognitive task while walking through a virtual world. Various secondary tasks have demonstrated the interaction effects between cognitive demands and locomotion. Different experiments have used speech as the distraction task [10], and others have used secondary tasks based on intentional movements involving a motor or muscular component [19] or even electrical stimulation [26]. For instance, using a counting-backwards task, effects on locomotion were observed in older adults, but not in young adults [4]. Cognitive costs of locomotion are observed via dual-tasking, for example, by studying changes in speed, cadence, step-length and double support time while engaged in secondary tasks. Observed decrements in locomotion performance are presumed to be caused by a limited attentional capacity depending on the complexity of the concurrent task [20].

This hypothesis is supported by experiments by Zanbaka et al. [39], who have shown that using certain near-natural locomotion interfaces can be cognitively demanding. Nadkarni et al. [20] have shown that cognitive tasks which activate working memory and spatial attention can have an effect on human locomotion. In particular, they found that changes in gait, including speed, stride length, and double support time, were affected by cognitive tasks. In experiments by Marsh et al. [18], the dual-task selective-interference paradigm was implemented to analyze the impact of spatial and verbal cognitive tasks on locomotion. They compared the cognitive resource demands of locomotion user interfaces that varied in their naturalness as well as the impact of a restricted field of view (FOV) on cognitive working memory demands while moving in an IVE. Their results suggest that locomotion with a less natural interface can increase spatial working memory demands, and locomotion with a smaller FOV can increase general attentional demands.

3 Experiment

As discussed above, the application of redirected walking in IVEs may not only be noticeable, but can induce cognitive demands on the user that are competing with other tasks for finite cognitive resources. In this section we describe the experiment in which we analyzed such a mutual influence between redirected walking and two different (spatial and verbal) cognitive tasks.

3.1 Participants

16 subjects (11 female and 5 male, ages 19 – 45, M=27.6) participated in the experiment. The participants were students or members of the local department of computer science, who obtained class credit for their participation. All of our participants had normal or corrected-to-normal vision. Two participants wore glasses and four participants wore contact lenses during the experiment. None of our participants reported a disorder of equilibrium. One of our participants reported a slight red-green weakness. No other vision disorders have been reported by our participants. Ten participants had participated in an experiment involving head-mounted displays (HMDs) before. We measured the interpupillary distances (IPDs) of our participants before the experiment [37]. The IPDs of our participants ranged between 5.6–6.7cm (M=6.3cm, SD=0.3cm). We used the IPD of each participant to provide a correct perspective on the HMD. Participants were naïve to the experimental conditions. The total time per participant, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing, was 1 hour. Participants wore the HMD for approximately 45 minutes. They were allowed to take breaks at any time.

3.2 Materials

We performed the experiment in a 12m×5m darkened laboratory room. As illustrated in Figure 1, subjects wore a wireless Oculus Rift DK1 HMD for the stimulus presentation, which provides a resolution
of 640×800 pixels per eye with a refresh rate of 60Hz and an approximated 110° diagonal field of view. We attached an active infrared marker to the HMD and tracked its position within the laboratory with a WorldViz Precision Position Tracking PPT-X4 active optical tracking system at an update rate of 60Hz with sub-millimeter precision for position data in the laboratory. The head orientation was tracked with an InertiaCubeBT sensor at 180Hz update rate, which we attached to the HMD. We compensated for inertial orientation drift by incorporating the PPT-X4 optical heading plugin. The visual stimulus consisted of a simple VE with grass, trees and pavement (see Figure 1). We used an Asus WA VI wireless kit to transmit the rendered images at 60Hz from a rendering computer to the HMD. As claimed by the manufacturers, not more than 2ms latency are introduced due to the wireless connection. The HMD and wireless transmitter box were powered by an Anker Astro Pro2 portable battery. The boxes were carried in a small belt bag. For rendering, system control and logging we used an Intel computer with 3.4GHz Core i7 processor, 16GB of main memory and two Nvidia GeForce 780Ti SLI graphics cards. The stimuli were rendered with the Unity 3D Pro engine. In order to focus participants on the task no communication between experimenter and subject was performed during the experiment. Task instructions were presented via slides on the HMD during the experiment. Participants performed the cognitive tasks via button presses on a Nintendo Wii remote controller. Participants wore fully-enclosed Sennheiser RS 180 wireless headphones during the experiment. We used the headphones to render forest and nature sounds, which minimized the ability of participants to estimate their physical position and orientation in the laboratory via ambient noise. The participants received auditory feedback in the form of a clicking sound when they pressed a button on the Wii remote controller.

### 3.3 Methods

We used a 3×3×2 dual-task within-subjects experimental design. We tested 3 cognitive conditions (i.e., verbal task, spatial task, and no task), and 9 locomotion conditions (i.e., redirected walking with curvature gains [31] \(g_R \in \{-0.1, -0.5, -1.0, -1.5, -2.0, 0, 1.0, 1.5, 2.0\}\), with 2 repetitions each. Thus, the experiment conditions included a single-task walking condition, and two dual-task conditions (walking plus either spatial or verbal working memory task). We maintained a fixed order of the cognitive conditions, but randomized the locomotion conditions. This ensured that none of the cognitive tasks would be favored due to potential training effects (see also [17]).

Before the experiment, all participants filled out an informed consent form and received detailed instructions on how to perform the cognitive tasks. Furthermore, they filled out the Kennedy-Lane simulator sickness questionnaire (SSQ) [14] immediately before and after the experiment, further the Slater-Usoh-Snead (SUS) presence questionnaire [36], and a demographic questionnaire. Every participant practiced each of the cognitive conditions four times before the experiment started, twice while standing in the VE, and twice during redirected walking with randomized gains. In total, participants completed 12 training trials.

#### 3.3.1 Locomotion Tasks

For each trial, participants were instructed to direct their gaze to a target sign displayed in front of them on the virtual pavement (see Figure 1). The target moved at a speed of 0.55m/s along the path in the VE during the experiment trials. In the locomotion conditions, participants were instructed to follow the leading target while maintaining the initial distance of 2m, similar to the task used by Neth et al. [21]. The total distance walked was 7m over a duration of 12.6s, after which the trial ended, and participants were guided to the next start position in the laboratory by aligning two markers in an otherwise blank 2D view. The next trial started once participants reached the new start position and indicated that they were ready to start by pressing a button on the Wii remote controller.

While participants were walking along the virtual pavement, we applied different curvature gains [31]. These gains exploit the fact that when users walk straight ahead in the virtual world, iterative injections of reasonably small camera rotations to one side force them to walk along a curved path in the opposite direction in the real world in order to stay on a straight path in the VE. Curvature gains \(g_R \in \mathbb{R}\) define the ratio between translations and applied virtual scene rotations, i.e., they describe the bending of the user’s path in the real world. The bending is determined by a segment of a circle with radius \(r \in \mathbb{R}^+\), as illustrated in Figure 1. Curvature gains are expressed by \(g_C = \frac{1}{r}\) with \(g_C = 0\) for real walking with \(r = \infty\). Gains \(g_C < 0\) less than zero correspond to counterclockwise circular movements, whereas gains greater than zero correspond to clockwise circular movements in the physical workspace. If the injected manipulations are reasonably small, users will accurately compensate for the virtual rotations and walk along a curved path. Curvature gains \(|g_C| \in [0, 0.045]\) are considered undetectable for users, which corresponds to radii of at least 22 meters (cf. [31]). We tested gains \(g_C \in [-\frac{1}{5}, \frac{1}{5}, \frac{1}{10}, \frac{1}{15}, \frac{1}{20}, 0]\), i.e., each curvature was tested both in clockwise and in counterclockwise direction. The tested gains correspond to circular radii that fit within laboratories with a walking area of 5m×5m, 10m×10m, 20m×20m, or 30m×30m, respectively.

In the experiment we evaluated lateral head movements when walking straight ahead along the path in the VE, which provides indications on how locomotion behavior is affected by redirected walking.

#### 3.3.2 Cognitive Tasks

To analyze the cognitive resource demands of redirected walking we considered verbal and spatial working memory tasks. Participants registered their responses on the cognitive tasks (detailed below) by pressing a button on the Wii remote controller. The display duration for every stimulus in the verbal as well as spatial cognitive tasks was set to 500ms with a pseudo-randomized interstimulus interval of 1100–1500ms similar to Baumann et al. [3], thereby allowing for 6 stimuli for every trial with 4 recorded responses. Participants were instructed to perform the cognitive task to the best of their ability while maintaining the distance to the leading target by walking behind the target in the locomotion dual-task conditions. Our dependent variable was the percentage of correct responses in the cognitive tasks, which indicates how the cognitive tasks are affected by redirected walking.

**Verbal two-back working memory task**

As illustrated in Figure 2(a), the verbal working memory task was a letter two-back task [10]. In every trial, participants were shown a con-
tinuous stream of letters that were flashed on the virtual target surface in the VE. The close distance of the target to the user ensured always good readability. Participants were instructed to respond by pressing the button on the Wii remote if a presented letter was the same as the one that came up two stimuli back in the sequence (true condition in Figure 2(a)). This task has a high verbal working memory load since it requires continuous on-line monitoring and maintenance of the presented letter until two consecutive letters appeared. If (and only if) the stimulus matched the one that came up two stimuli before it, participants had to press a button on the Wii remote. This task did not require large shifts of spatial attention or memory as the letters continuously appear in the center of the target surface.

Spatial two-back working memory task
As illustrated in Figure 2(b), the spatial working memory task examined covert shifts of spatial memory and attention. In every trial, participants were shown a continuous stream of T-shaped symbols that were flashed on a virtual target surface in the VE. The stimulus appeared in one of the four corners of the target surface rotated by $\Theta \in \{\frac{1}{4} \pi, \frac{1}{2} \pi, \frac{3}{4} \pi, \frac{5}{4} \pi\}$ radians. Participants responded by pressing a button on the Wii remote if a presented symbol was oriented in the same way as the one that came up two stimuli back in the sequence (true condition in Figure 2(b)). This task did not require large verbal working memory. The displayed symbols are considered hard to verbalize (cf. [3]).

4 Results

We found no effect of walking clockwise or counterclockwise along the circular paths and therefore pooled the data. Figure 3 shows the pooled results for the tested curvature gains plotted against the performance in the locomotion and cognitive tasks. The vertical bars show the standard error of the mean. The colored lines show the results for the verbal task, spatial task, or condition without cognitive task. The x-axes show the standard deviation of lateral movements in Figure 3(a), and the percentage of correct responses in the cognitive tasks in Figure 3(b).

The results were normally distributed according to a Shapiro-Wilk test at the 5% level. We analyzed the results with a repeated-measures ANOVA and Tukey multiple comparisons at the 5% significance level with Bonferroni correction. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly’s test indicated that the assumption of sphericity had been violated.

4.1 Locomotion Performance

We observed low lateral sway, i.e., lateral movements of the participants during forward walking, without redirected walking manipulations and without cognitive tasks, which was indicated by a standard deviation in lateral head movements of M=0.042m, SD=0.0058m. Increased lateral head or body movements are a common occurrence in old adults, for whom increased lateral instability during walking is hypothesized to cause more compensatory lateral movements. Since strong redirected walking manipulations require users to consciously compensate for lateral and rotational changes during virtual straightforward walking [8], we hypothesized that we would find similar effects in our experiment. Indeed, lateral sway increased for both cognitive tasks as well as for larger curvature gains.

We found a significant main effect of curvature gain on the standard deviation of lateral movements ($F(1,487)=22.307; p<0.001, \eta^2_g=0.694$). Post-hoc tests showed that the lateral sway between each two curvature gains was significantly different with larger gains corresponding to larger sway ($p<0.05$, except between $g_C=0$ and $|g_C|=\frac{1}{15}$ ($p=0.66$) as well as between $|g_C|=\frac{1}{10}$ and $|g_C|=\frac{1}{5}$ ($p=0.45$).

In addition, we found a significant main effect of cognitive task on the standard deviation of lateral movements ($F(2,30)=1.993, p<0.001, \eta^2_g=0.444$). Post-hoc tests showed that the lateral sway was significantly higher with the spatial task compared to no task ($p=0.001$), as well as with the verbal task compared to no task ($p=0.013$), but not between the spatial task and the verbal task ($p=0.621$). Both cognitive tasks exhibited similar effects on lateral sway.

We did not find a significant interaction effect between cognitive task and curvature gain on the standard deviation of lateral movements ($F(2,970)=4.545)=1.598, p=0.20, \eta^2_p=0.094$).

4.2 Cognitive Performance

We observed high task performance without redirected walking manipulations both for the spatial task (M=947, SD=0.50) and the verbal task (M=981, SD=0.36). Task performance was decreased for both cognitive tasks for larger curvature gains.

We found a significant main effect of curvature gain on the percentage of correct responses ($F(2,758)=41.370)=10.887, p<0.001, \eta^2_g=0.421$). Post-hoc tests showed no significant differences between each two curvature gains ($p>0.05$).

Moreover, we compared the percentage of correct responses for the spatial and the verbal task with a paired t-test. We found a significant main effect of the cognitive task on the percentage of correct responses between the spatial task and the verbal task ($p<0.001$). Participants made significantly more errors in the spatial task compared to the verbal task.

We found a significant interaction effect between cognitive task and curvature gain on the percentage of correct responses ($F(3,557)=53.357)=3.419, p<0.02, \eta^2_g=0.186$). For the verbal task, the results show a significant lower percentage of correct responses for the largest tested curvature gain $|g_C|=\frac{1}{15}$ compared to all other gains except for $|g_C|=\frac{1}{2}$. In particular, post-hoc tests showed for the verbal task a significant lower percentage of correct responses for curvature gain $|g_C|=\frac{1}{25}$ compared to curvature gain $g_C=0$ ($p<0.001$), for curvature gain $|g_C|=\frac{1}{25}$ compared to curvature gain $|g_C|=\frac{1}{15}$ ($p=0.04$), as well as for curvature gain $|g_C|=\frac{1}{25}$ compared to curvature gain $|g_C|=\frac{1}{10}$ ($p=0.027$). For the spatial task, the results show a significant lower percentage of correct responses for curvature gain $|g_C|=\frac{1}{25}$ compared to curvature gain $g_C=0$ ($p=0.013$), as well as for curvature gain $|g_C|=\frac{1}{25}$ compared to curvature gain $g_C=0$ ($p<0.001$).

4.3 Questionnaires

We measured a mean SUS-score of M=13.2 (SD=15.2) before the experiment, and a mean SUS-score of M=47.4 (SD=60.8) after the experiment. The results indicate a typical increase in simulator sickness for extensive walking with an HMD over the time of the experiment. The mean SUS-score for the sense of feeling present in the VE was M=4.71 (SD=8.7), which indicates a high sense of presence [36]. The participants judged their fear to collide with physical obstacles during the experiment as comparably low (rating scale, 0=no fear, 4=high fear, M=1.33, SD=1.23), which is often not the case in redirected walking implementations.
5 DISCUSSION

The results of the experiment show a significant influence of redirected walking on verbal as well as spatial working memory tasks, and we also found a significant effect of cognitive tasks on walking behavior. According to [31] a straight path in the VE can be turned into a circular arc in the real world with a radius of approximately 22 meters, while users are still not able to reliably detect the manipulation. This corresponds to a curvature gain of $|g_{C}| = \frac{1}{10}$. Our experiments showed a significant increase of lateral sway for both spatial task as well as verbal task for gains larger than $|g_{C}| = \frac{1}{10}$. Furthermore, we also found that the task performance was decreased for both cognitive tasks again for gains larger than $|g_{C}| = \frac{1}{10}$. Hence, only at gains where users are clearly able to detect the manipulation, cognitive task performance for spatial as well as verbal tasks decreases, and in addition lateral sway increases when users are challenged with cognitive tasks.

These are important findings for the application of redirected walking techniques. The results show that large redirected walking manipulations require additional cognitive resources by the user which are competing for finite cognitive resources. With increasing amounts of manipulations, the required cognitive resources also increase. If manipulation with curvature gains larger than $|g_{C}| = \frac{1}{10}$ are applied, users are clearly able to detect the manipulation. However, more importantly, for such curvature gains, cognitive task performance for spatial as well as verbal tasks decreases, and lateral sway also increases when users are challenged with cognitive tasks. Based on our results, we cannot recommend to apply redirected walking with curvature gain manipulations in VR laboratories with a size below 10m×10m in case users have to perform complex cognitive tasks. If possible, VR developers should apply curvature gain manipulations below the detection thresholds of $|g_{C}| = \frac{1}{10}$. If redirected walking is to be applied in smaller VR laboratories, we recommend combining curvature gains with rotation and translation gains to minimize the magnitude of manipulations (e.g., see [15, 23, 31, 34]).

6 CONCLUSIONS

In this article we presented an experiment in which we evaluated the mutual influence between redirected walking and verbal as well as spatial working memory tasks in VR laboratories. We analyzed how curvature gains correlate with spatial and verbal working memory demands. The results of the experiment showed a significant influence of redirected walking on verbal as well as spatial working memory tasks, and we also found a significant effect of cognitive tasks on walking behavior. We discussed the implications and provided guidelines for using redirected walking in VR laboratories.

For future work, we suggest comparative analyses of cognitive demands of redirected walking with other locomotion techniques such as in-place walking or 3D traveling techniques based on joysticks or gamepads.

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REFERENCES


