Redirecting Walking and Driving for Natural Navigation in Immersive Virtual Environments

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Abstract—Walking is the most natural form of locomotion for humans, and real walking interfaces have demonstrated their benefits for several navigation tasks. With recently proposed redirection techniques it becomes possible to overcome space limitations as imposed by tracking sensors or laboratory setups, and, theoretically, it is now possible to walk through arbitrarily large virtual environments. However, walking as sole locomotion technique has drawbacks, in particular, for long distances, such that even in the real world we tend to support walking with passive or active transportation for longer-distance travel. In this article we show that concepts from the field of redirected walking can be applied to movements with transportation devices. We conducted psychophysical experiments to determine perceptual detection thresholds for redirected driving, and set these in relation to results from redirected walking. We show that redirected walking-and-driving approaches can easily be realized in immersive virtual reality laboratories, e. g., with electric wheelchairs, and show that such systems can combine advantages of real walking in confined spaces with benefits of using vehicle-based self-motion for longer-distance travel.

Index Terms—Redirected walking, redirected driving, natural locomotion, self-motion perception.

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1 INTRODUCTION

Immersive virtual environments (VEs) are often characterized by head-mounted displays (HMDs) or immersive projection technologies, as well as a tracking system for measuring head position and orientation data. Navigation in such immersive VEs is often performed with interaction devices, such as joysticks or wands, which allow users to initiate self-motion in virtual scenes, but often provide unnatural inputs and feedback from the body about virtual self-motion. Although such setups can provide users with a sense of moving through three-dimensional virtual scenes, these *magical* forms of virtual self-motion [4] have often revealed degraded performance in wayfinding tasks and mental map buildup when compared to *natural* forms of self-motion from the real world [25, 28].

In the real world, we navigate with ease by walking, running, driving etc., but in immersive VEs realistic simulation of these forms of self-motion is difficult to achieve. While moving in the real world, sensory information such as vestibular, proprioceptive, and efferent copy signals as well as visual information create consistent multi-sensory cues that indicate one's own motion, i. e., acceleration, speed and direction of travel. Traveling through immersive virtual environments by means of *real walking* is considered the most basic and intuitive way of moving within the real world, and is an important activity to increase the naturalness of virtual reality (VR)-based interaction [30]. Keeping such a dynamic ability to navigate through large-scale immersive VEs is of great interest for many 3D applications, such as in urban planning, tourism, or 3D entertainment. However, natural self-motion in immersive VEs imposes significant practical challenges [33].

An obvious approach for leveraging natural self-motion for immersive VEs is to transfer the user's tracked head movements to changes of the camera in the virtual world by means of isometric mappings. 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. This technique has the drawback that a user's movements are restricted by a limited range of the tracking sensors and a rather small workspace in the real world. The size of the virtual world often differs from the size of the tracked laboratory space so that a straightforward implementation of omni-directional and unlimited walking is not possible. Thus, virtual locomotion methods are required that enable locomotion over large distances in the virtual world while remaining within a relatively small workspace in the real world.

As a solution to this challenge, researchers transferred findings from the field of perceptual psychology to address the space limitations of immersive VR setups. Based on perceptual studies showing that vision often dominates proprioception and vestibular sensation when the senses disagree [2, 8], researchers found that users tended to unwittingly compensate with their body to small inconsistencies in visual stimulation while walking in immersive VEs, which even allows guiding users along paths in the real world that differ from the perceived path in the virtual world [23]. In principle, using this *redirected walking* it becomes possible to explore arbitrarily large virtual scenes using redirection techniques, while the user is guided along circular paths in a considerably smaller tracked interaction space in the laboratory. Recent studies on navigation and spatial disorientation in confined virtual spaces suggest that redirected walking can provide users with similar benefits for navigation as real walking, and a significantly improved performance over virtual flying and other travel techniques [22, 29].

However, although (redirected) walking is a simple navigation technique, it has practical drawbacks, in particular, when traveling over long distances. Even in the real world we support long-distance travel by various forms of traveling devices. Thus, in this article we propose supporting natural movements in immersive VEs by moving with traveling devices in the real world (e. g., electric wheelchairs or scooters). Although such devices can make it more comfortable to travel long distances in VEs, while supporting natural vestibular and proprioceptive feedback, using traveling devices that move in the real world imposes the same problems in terms of space restrictions as real walking. Therefore, concepts similar to redirected walking may be applied to redirect a user's path of travel using such devices. However, since users receive different self-motion cues from the real and virtual world during walking and driving it has to be carefully analyzed whether or not and to what extent redirection techniques can be applied when users steer such traveling devices.

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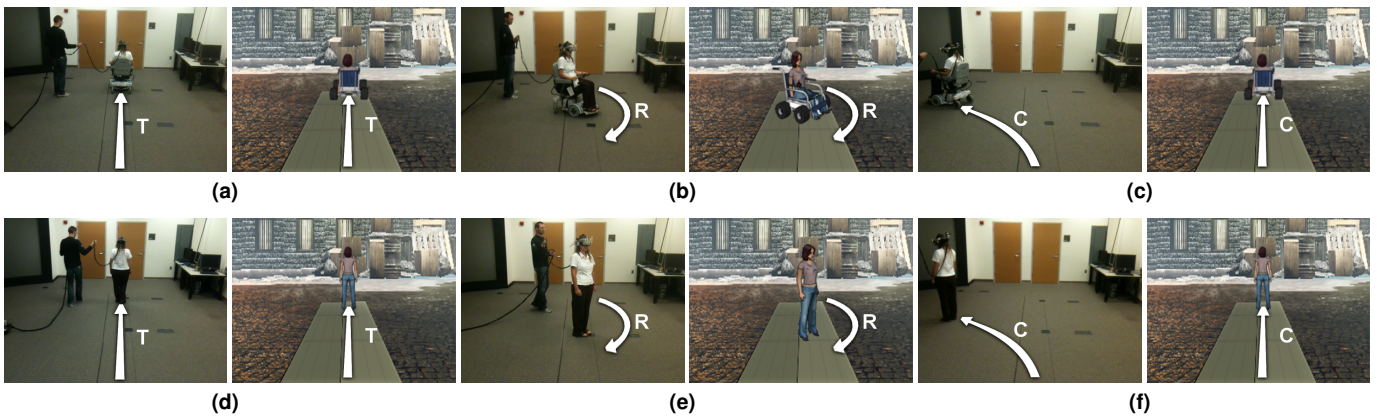
Fig. 1. Redirected walking-and-driving in immersive virtual environments: (a)-(c) user steering an electric wheelchair with a head-mounted display in the virtual reality laboratory, and (d)-(f) real walking counterparts. The renderings illustrate virtual representations of translations (T), rotations (R) and physical curvatures (C) [27].

In this article we propose, evaluate and discuss *redirected walking-and-driving*, which allows users of immersive VEs to cover long distances in realistic virtual scenes with near-natural vestibular and proprioceptive feedback by steering a traveling device, while retaining the ability to switch to walking depending on the navigation requirements, similar to the real world. In particular, we show that redirected driving can easily be incorporated in head-tracked immersive virtual reality laboratories by adapting an electric wheelchair for virtual traveling.

The remainder of this article is structured as follows. Section 2 provides an overview of virtual self-motion. In Section 3 we present redirected driving in a head-tracked VR laboratory. In Section 4 we describe psychophysical experiments that we conducted to determine perceptual differences in the detectability of manipulations of translations and rotations when walking or driving in a virtual scene. Section 5 concludes the article and gives an overview of future research.

2 BACKGROUND

Moving through a virtual scene is one of the most essential interaction tasks in virtual reality environments, for which various different technologies and techniques have been introduced. Virtual self-motion approaches can be divided in *locomotion* and *traveling* user interfaces.

Locomotion and Traveling

Defined as active self-propulsion, locomotion encompasses repetitive motions of legs and body during walking, but also propulsion of human-powered vehicles like bicycles, scooters, skaters, or manual wheelchairs [13]. In particular, the key characteristic of locomotion that distinguishes it from passive motion is that proprioceptive and kinesthetic information from the body while moving can be integrated with visual self-motion cues by the perceptual system. A significant body of work has shown the benefits of proprioceptive cues of physical motion in spatial tasks [7, 25], with some disagreement about whether the motion needs to be walking [25] or whether simple physical rotation would suffice [24]. Results imply that perception of virtual geometry, motions and distances may be enhanced by the ability to locomote [13]. Moreover, the features of energy expenditure and sensorimotor integration are hypothesized to yield an increased sense of presence in immersive VEs [26]. Typical problems of locomotion interfaces are user exertion when moving over long distances, and the limited physical space when transferring actual movements of a user from a real-world laboratory to a potentially infinite VE.

Traveling user interfaces encompass approaches that are not based on repetitive limb or body motions for initiating or controlling movements. Examples are virtual steering techniques which combine head orientation tracking with hand-based input, e. g., with wands or joysticks, to initiate translations of the user's virtual viewpoint. Since users receive conflicting sensory information caused by visually indi-

cated motions that are not matched by proprioceptive and vestibular cues from their body, such approaches may limit the user's sense of feeling present in a VE [26]. To provide a cognitive grounding for virtual traveling techniques, and to provide physical self-motion cues when traveling in a virtual scene, motion simulators can be used. Motion simulators consist of a mockup of a real-world vehicle, such as a car or aircraft, which may be steered by the user, while receiving visual feedback about the motions, as well as vestibular and proprioceptive feedback from a motion platform [35]. Motion platforms used in simulators represent a mature technology area that is not addressed in this article. In contrast to simulating movements in the real world with motion simulators, we propose using vehicles that actually move in the physical world, and are steered by the user. Examples for such motion devices include electric wheelchairs, scooters, roller skaters, and bicycles. With such devices, users receive consistent multisensory cues about self-motions in the virtual and real world, including visual, vestibular and inertial feedback, while limiting user exertion when traveling over long distances. However, the same limitations apply to users moving with a vehicle through the laboratory space as for users walking in the limited workspace provided by tracking sensors.

Redirection Techniques

Different approaches to redirect a user in immersive VEs have been proposed. An obvious approach is to scale translational movements, for example, to cover a virtual distance that is larger than the distance traveled in the physical space. With most redirection techniques, however, the virtual world is slowly rotated around the center of a standing or walking user until the user is oriented in such a way that no physical obstacles block the path of travel [12, 17, 22, 23]. For instance, if the user wants to walk straight ahead for a long distance in the virtual world, small rotations of the camera redirect the user to walk unconsciously on an arc in the opposite direction in the real world. When redirecting a user, the visual sensation is consistent with motion in the VE, but vestibular and proprioceptive sensations reflect motion in the physical world. If the induced manipulations are small enough, the user has the impression of being able to walk in the virtual world in any direction without restrictions. A vast body of research has been undertaken in order to identify thresholds that indicate the tolerable amount of deviation between sensations from the virtual world and physical world while the user is walking. In this context, Steinicke et al. [27] conducted a series of psychophysical experiments to identify detection thresholds for redirected walking gains. Therefore, they compared manipulations with a range of gains, which have been applied to rotations, translations, and curved paths, while subjects had to discriminate between virtual and real motions (see Figure 1).

In this article, we show that redirection techniques can be applied not only for locomotion, but also for traveling, with a user steering a physical vehicle that actually moves through the laboratory space.

3 REDIRECTED DRIVING

Redirected driving for moving vehicles in a limited VR laboratory space can be implemented with the same approaches as used to enable redirected walking. In particular, since redirection is a software-based process that makes use of perceptual limitations of humans with the goal to subconsciously affect a user's movements in the real world compared to virtual movements, many of the controllers developed for redirected walking can be directly applied for manipulating a user's movements when steering a vehicle [23, 27].

Redirection of walking and driving differs in terms of different cues provided to users about movements in the real and virtual world. For instance, walking users may adapt to manipulations of the visual stimuli, e. g., optic flow movement velocity and direction cues [6, 11, 18], in the VE by adaptation of muscles used for walking straight, or turning [23]. Adaptation of traveling direction and velocity of users driving with a vehicle may require different muscle groups, which are integrated with different couplings and levels of conscious access to motor control information in human perception and action processes [9].

3.1 Combining Walking and Driving

Redirected walking-and-driving can be implemented with the same software-based techniques, and even in the same VR setup. In particular, provided the user's head position and orientation can be tracked in the VR laboratory, basic mappings from real head movements to virtual camera motions are independent of whether the user is using a vehicle in the real world to travel, or whether the user is walking (see Figure 1). As a result, for basic setups no additional hardware is required to enable combined walking-and-driving. However, if users are immersed in a VE using a HMD, the virtual scene is displayed exclusively to the user, while blocking visual information about the vehicle from the real world, i. e., it may be required to track the position and orientation of the vehicle in the laboratory to display a registered virtual counterpart to the user when required (see Figures 1(a)-(c)). Combining walking-and-driving in VR environments provides users with advantages of walking in focus regions, as well as an intuitive means of traveling over longer distances.

3.2 Redirecting Self-Motion

In head-tracked immersive VR environments user movements are typically mapped isometrically to virtual camera motions. For each frame the change in position and orientation measured by the tracking system is used to update the virtual camera state for rendering the new image that is presented to the user. The new camera state can be computed from the previous state defined by tuples consisting of the position $pos_n \in \mathbb{R}^3$ and orientation $(yaw_n, pitch_n, roll_n) \in \mathbb{R}^3$ at frame $n \in \mathbb{N}$ in the scene with the tracked change in position $\Delta pos \in \mathbb{R}^3$ and orientation $(\Delta yaw, \Delta pitch, \Delta roll) \in \mathbb{R}^3$. In the general case, we can describe a scaled mapping from real to virtual motions as follows:

$$pos_{n+1} = pos_n + g_T \cdot \Delta pos,$$

$$\begin{cases} yaw_{n+1} = yaw_n + g_{R[yaw]} \cdot \Delta yaw, \\ pitch_{n+1} = pitch_n + g_{R[pitch]} \cdot \Delta pitch, \\ roll_{n+1} = roll_n + g_{R[roll]} \cdot \Delta roll, \end{cases}$$

with translation gains $g_T \in \mathbb{R}$ and rotation gains $(g_{R[yaw]}, g_{R[pitch]}, g_{R[roll]}) \in \mathbb{R}^3$ [27]. As discussed by Interrante et al. [15], translation gains may be selectively applied to translations in the main walk direction.

Camera rotations can also be introduced relative to head translations. In particular, if the virtual scene is slowly rotated around the user's viewpoint while the user is walking straight, the user adapts to the virtual rotation by rotating in the real world. Such physical path bending manipulations are specified as rotation angles per walking distance [23], or circular path radii in the real world [27], with curvature gains defined as $g_C = \frac{1}{r}$, for radius $r \in \mathbb{R}^+$, and $g_C = 0$ for $r = \infty$.

High-level redirected walking controllers usually incorporate one or more of these techniques to manipulate a user's walking direction or travel distance in the real world relative to the VE [5, 21, 22, 23]. To support this process, researchers determined the amount of manipulation that users are unaware of for each of these techniques in the field of redirected walking [27], such that controllers could try to determine the least noticeable combination of the manipulations in the context of the user's current state in the real laboratory and virtual scene.

3.3 Hypothesis

Since previous research on detectability of redirection manipulations has focused mainly on users walking with a HMD in a laboratory environment, it is still largely unknown how the human perceptual system integrates differences in self-motion information from the real and virtual world when steering a traveling device, such as when seated in an electric wheelchair. However, diverging findings in the fields of redirected walking and motion platforms suggest differences in discrimination performance and detectability of manipulations [14, 23, 32, 34]. In particular, it is not well-understood how the sophisticated perceptual processes involved in posture stability during natural walking contribute to self-motion perception, e. g., when coordinating over 50 muscles or muscle groups to maintain the body in a repetitive forward progression [3, 19], in comparison to seated traveling, which limits the number of available self-motion cues. We hypothesize that

H1) with an electric wheelchair subjects will be less accurate at detecting discrepancies of real and virtual self-motions,

which is suggested by a reduced number of real-world self-motion cues when seated compared to when walking, and suggests advantages of redirected driving over redirected walking for longer-distance traveling in a large virtual scene.

4 PSYCHOPHYSICAL EVALUATION OF REDIRECTED DRIVING

In this section we evaluate redirected driving in three experiments, which we conducted to analyze detectability of manipulations of translations and rotations when driving an electric wheelchair, and compare the results to redirected walking based on an implementation of the same redirection techniques. Therefore, we analyzed subjects' estimation of physical movements compared to simulated virtual motions while varying the parameters of the redirection techniques, which provides information on how the traveling technique affects the just noticeable difference between physical and virtual motions, as well as practical thresholds that can be applied in redirection controllers.

4.1 Experiment Design

We performed the experiments in a 11m×9.5m darkened laboratory room. The subjects wore an nVisor SX60 HMD (1280×1024@60Hz, 60° diagonal field of view) for the stimulus presentation. We used a 3rdTech Hiball 3100 Wide Area Tracker to track the position and orientation of an optical sensor that we fixed on the HMD. The Hiball tracker provided sub-millimeter precision and accuracy of position data, as well as $<0.01°$ angular precision and $<0.02°$ angular accuracy of orientation data at an update rate between $1000-2000$Hz during the experiments. For visual display, system control and logging we used an Intel computer with Core i7 processors, 6GB of main memory and Nvidia Quadro FX 1500 graphics card.

For the trials with electric wheelchair we used a Hoveround MPV 5 Power Wheelchair, which provides variable speed settings of up to 8 km/h, a 22.7" turning radius (adjustable by subjects to zero around the head position), and joystick control (see Figure 1). We used settings of approximately 2.34 km/h top speed, 0.13 m/s^2 acceleration and -0.83 m/s^2 deceleration for linear movements, as well as 44 deg/s top speed, 45 deg/s^2 acceleration and -90 deg/s^2 deceleration for angular movements. During the experiment, ambient city noise was presented to the subjects over the headphones in the nVisor SX60 HMD to reduce auditive orientation cues from the laboratory.

In order to focus subjects on the tasks no communication between experimenter and subject was performed during the experiments. All instructions were displayed on slides in the VE, and subjects judged their perceived motions via button presses on a Nintendo Wii Remote controller. The visual stimulus consisted of a virtual city environment rendered with Crytek's CryEngine 3 (see Figure 2).

Fig. 2. Visual stimulus generated with Crytek's CryEngine 3 in the walking and driving trials.

4.1.1 Participants

8 male and 4 female (ages $19-51$, $avg = 26.9$) subjects participated in the study. All subjects were undergraduate or graduate students, or members of the department of computer science. All had normal or corrected to normal vision. No subject had a disorder of balance. 1 subject had no experience with 3D games, 5 had some, and 6 had much experience. 5 of the subjects had experience with walking in a HMD environment. All subjects were naïve to the experimental conditions. All subjects had experience with steering the electric wheelchair using its joystick controller due to a 3-minute familiarization phase before the experiment. The total time per subject including pre-questionnaire, instructions, training, experiments, breaks, and debriefing was 1.5 hours, of which subjects spent approximately 1 hour wearing the HMD. Subjects were allowed to take breaks at any time.

4.1.2 Methods

We used a within-subject design, and the method of constant stimuli in a *two-alternative forced-choice* (2AFC) task. In the method of constant stimuli, the applied gains are not related from one trial to the next, but presented randomly and uniformly distributed. The subject chooses between one of two possible responses, e. g., "Was the virtual movement *smaller* or *larger* than the physical movement?"; responses like "I can't tell." are not allowed. When the subject cannot detect the signal, the subject is forced to guess, and will be correct on average in 50% of the trials [27].

The gains at which the subject responds "smaller" in half of the trials is taken as the *point of subjective equality* (PSE), at which the subject judges the virtual motion to match the physical movement. As the gain decreases or increases from this point the ability of the subject to detect the difference between physical and virtual motion increases, resulting in a psychometric curve for the discrimination performance. The discrimination performance pooled over all subjects is represented with a fitted psychometric function, for which we used the common Weibull function for 2AFCs [10, 16]. The PSEs give indications about how to parameterize the redirection technique such that virtual motions appear natural to users, while manipulations with values close to the PSEs will often go unnoticed by users. Typically, the points are taken as thresholds, at which the psychometric curve reaches the middle between the chance level and 100% correct detections (cf. Steinicke et al. [27]). We define the detection threshold (DT) for gains smaller than the PSE to be the point at which the subject has 75% probability of choosing the "smaller" response and the detection threshold for gains larger than the PSE to be the point at which the subject chooses the "smaller" response in only 25% of the trials (since the correct response was then chosen in 75% of the trials). The detection thresholds indicate which practical range of manipulations can be applied in redirection controllers.

We measured the subjects' sense of presence with the SUS questionnaire [31], and simulator sickness with the Kennedy-Lane SSQ before and after each experiment. The wheelchair and walking trials were conducted in separate blocks, of which the order was randomized between subjects. The order of the experiments in each condition was randomized for each subject.

4.2 Experiment E1: Rotation Discrimination

We analyzed the impact of the physical locomotion methods walking and driving with independent variable $g_{R[yaw]}$ (cf. Section 3) on discrimination of real and virtual rotations.

4.2.1 Materials

We instructed the subjects to turn their head and body around in the VE until the scene changed. The rotation angle in the real world was randomized between $67.5°$ and $112.5°$, with an average rotation angle of $90°$. The virtual rotation angle was scaled with rotation gains $g_{R[yaw]}$ between 0.4 and 1.6 in steps of 0.2. We randomized the independent variables over all trials, and tested each 4 times. In total, each subject performed 28 rotations in-place when standing, as well as when seated in the wheelchair. We instructed subjects to alternate clockwise and counterclockwise rotations, which were counterbalanced for all gains.

For each trial, after a subject performed the rotation in the VE, the subject had to decide whether the simulated virtual rotation was smaller (down button) or larger (up button) than the physical rotation with the Wii Remote controller. The next trial started immediately after the subject judged the previous motion. The procedure was identical for rotations when standing, and with the wheelchair. To control rotations with the wheelchair, subjects used the joystick to initiate a rotation either to the left or right, corresponding to counterclockwise and clockwise rotations, respectively. The physical rotation speed with the wheelchair of 44 deg/s approximated the mean turning speed of 41 deg/s while standing.

4.2.2 Results

Figure 3 shows the pooled results for the gains $g_{R[yaw]} \in \{0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6\}$ on the x-axis with the standard error over all subjects. The y-axis shows the probability for estimating the virtual rotation as smaller than the real rotation. The black psychometric function shows the results for standing subjects, and the gray function for subjects rotating with the wheelchair. We observed a chi-square goodness of fit of the psychometric function of $\chi^2 = 0.6990$ for standing, and $\chi^2 = 0.3822$ for the wheelchair. We did not observe a difference in responses for clockwise and counterclockwise rotations, as well as for the different physical rotation angles, and pooled the data. From the psychometric functions we determined PSEs at $g_{R[yaw]} = 0.9544$ for standing, and $g_{R[yaw]} = 1.0111$ for the wheelchair condition. A practically applicable range of manipulations with rotation gains is given as the interval between the lower and upper detection thresholds, which we determined from the psychometric functions as $g_{R[yaw]} \in [0.6810, 1.2594]$ for standing subjects, and $g_{R[yaw]} \in [0.7719, 1.2620]$ for the electric wheelchair.

4.2.3 Discussion

The results show a significant impact of parameter $g_{R[yaw]}$ on responses. For subjects standing and rotating in-place, the results approximate results found by Steinicke et al. [27]. In particular, the subjects' responses indicate a slight underestimation of rotations in the VE of approximately 4.56%, while Steinicke et al. found an underestimation of approximately 4%. For subjects rotating while seated in the electric wheelchair, the results indicate no bias towards over- or underestimation of virtual rotations. The detection thresholds in the standing condition define a possible manipulation range of rotations that can cause a real rotation to deviate from a fixed virtual rotation between -20.60% and $+46.84\%$ (see Section 3). In the wheelchair condition real rotations can deviate between -20.76% and $+29.55\%$.
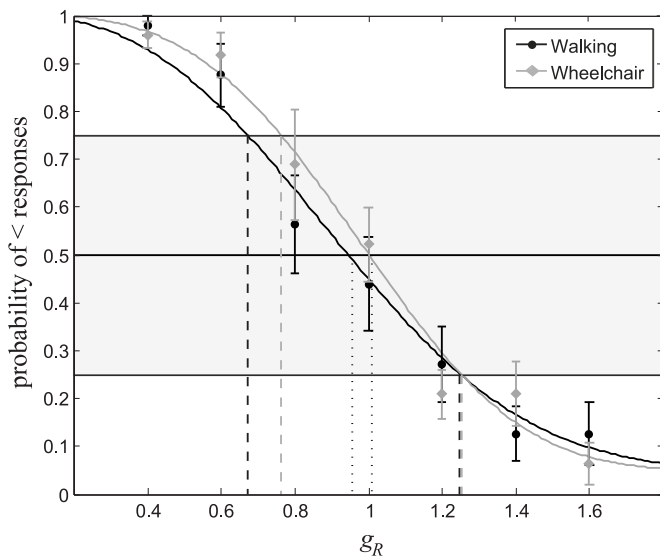
Fig. 3. Pooled results of in-place rotations while standing (black function), and seated in the wheelchair (gray function). The x-axis shows the applied parameter $g_{R[yaw]}$. The y-axis shows the probability of estimating the virtual rotation as smaller than the real rotation.

Fig. 4. Pooled results of translations while walking (black function), and driving in the wheelchair (gray function). The x-axis shows the applied parameter g_T. The y-axis shows the probability of estimating the virtual translation as smaller than the real translation.

The results are interesting, in particular, considering the duality of movement cues provided from the real and virtual world during rotations. From the VE, subjects primarily received visual cues, e. g., optic flow [18], as well as limited cues from ambient auditive sources of city noise. From the real world, subjects in both conditions received vestibular feedback about their angular head motion. Differences between the two conditions mainly show for proprioceptive feedback. While standing subjects received proprioceptive cues about the motion of their body, such cues were limited in the wheelchair condition. Moreover, subjects had to initiate rotations by pushing the joystick of the wheelchair all the way to the left or right to initiate counterclockwise or clockwise rotations, respectively. This suggests that subjects got the same proprioceptive cues about the state of their hand in all trials, independent of the virtual motion. It remains unclear if the differences in the responses were caused by cue integration processes [9], or cognitive effects of the traveling technique [1].

4.3 Experiment E2: Translation Discrimination

We analyzed the impact of the physical locomotion methods walking and driving with independent variable g_T (cf. Section 3) on discrimination of real and virtual travel distances.

4.3.1 Materials

We instructed the subjects to walk or drive forward along a displayed straight path in the virtual scene until the scene changed (see Figure 2). The travel distance in the real world was randomized between $2.5-3.5$m. The virtual travel distance was scaled with translation gains g_T between 0.4 and 1.6 in steps of 0.2. As proposed by Interrante et al. [15], we applied translation gains only to translations in the main walk direction, i. e., we did not scale lateral translations and head bobbing. We randomized the independent variables over all trials, and tested each 4 times. In total, each subject performed 28 translation trials when walking, as well as when driving with the wheelchair.

For each trial, after a subject performed the translation in the VE, the subject had to decide whether the simulated virtual translation was smaller (down button) or larger (up button) than the physical translation with the Wii Remote controller. After the subject judged the previous motion, subjects were guided to the start position in the real world for the next trial via two 2D markers on a uniform background. The next trial started immediately once the subject assumed the start position and orientation for the next trial. The procedure was identical for translations when walking, and translations in the wheelchair. To
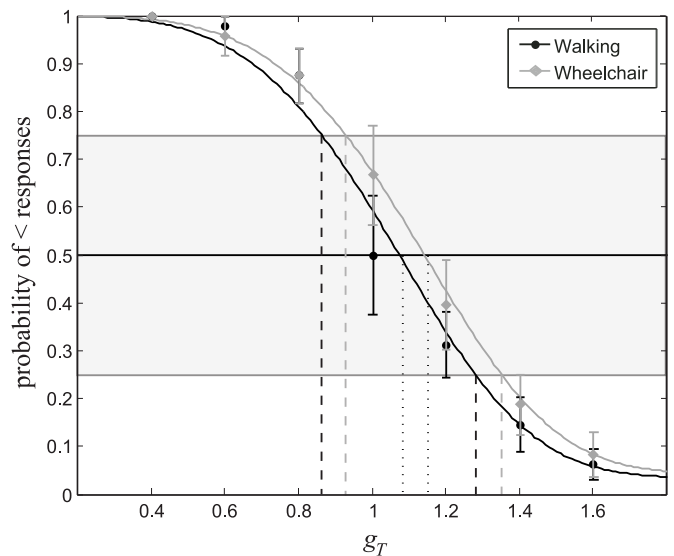
control translations with the wheelchair during the trials, subjects used the joystick to initiate a straight translation in forward traveling direction. The physical traveling speed with the wheelchair of 2.34 km/h approximated the mean walking speed of 2.7 km/h.

4.3.2 Results

Figure 4 shows the pooled results for the gains $g_T \in \{0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6\}$ on the x-axis with the standard error over all subjects. The y-axis shows the probability for estimating the virtual translation as smaller than the real translation. The black psychometric function shows the results for walking subjects, and the gray function for subjects traveling with the wheelchair. We observed a chi-square goodness of fit of the psychometric function of $\chi^2 = 0.5372$ for walking, and $\chi^2 = 0.0258$ for the wheelchair. We did not observe a difference in responses for the different physical traveling distances, and pooled the data. From the psychometric functions we determined PSEs at $g_T = 1.0824$ for walking, and $g_T = 1.1508$ for driving with the wheelchair. A practically applicable range of manipulations with translation gains is given as the interval between the lower and upper detection thresholds, which we determined from the psychometric functions as $g_T \in [0.8724, 1.2896]$ for walking, and $g_T \in [0.9378, 1.3607]$ for driving with the electric wheelchair.

4.3.3 Discussion

The results show a significant impact of parameter g_T on responses. For walking subjects, the results approximate results found by Steinicke et al. [27]. In particular, the subjects' responses indicate a slight overestimation of translations in the VE of approximately 8.24%, while Steinicke et al. found an overestimation of approximately 7%. For subjects driving with the electric wheelchair, the results indicate a stronger bias towards overestimation of virtual rotations of approximately 15.08%. The detection thresholds in the walking condition define a possible manipulation range of translations that can cause a real translation to deviate from a fixed virtual translation between -22.46% and $+14.62\%$ (see Section 3). In the wheelchair condition real translations can deviate between -26.51% and $+6.63\%$.

Different cues provided from the real and virtual world during walking and driving may have caused the differences. Subjects received visual cues about translations in the VE, as well as limited cues from ambient city noise. Subjects in both conditions received vestibular feedback about their linear head motion in the real world. Similar

to experiment E1 (see Section 4.2), differences between the two conditions mainly show for proprioceptive feedback during translations. While walking subjects received proprioceptive cues about the motion of their body, such cues were limited in the wheelchair condition. Subjects driving the wheelchair had to initiate translations by pushing the joystick all the way forward to initiate linear movements. This suggests that subjects got the same proprioceptive cues about the state of their hand in all trials, independent of virtual translations.

4.4 Experiment E3: Curvature Discrimination

We analyzed the impact of the physical locomotion methods walking and driving on discrimination of real and virtual motion directions.

4.4.1 Materials

The procedure was similar to Experiment E2 (see Section 4.3). We instructed the subjects to walk or drive forward along a displayed straight path in the virtual scene until the scene changed. While a subject was moving forward along the virtual path, we slowly rotated the virtual camera around the subject's virtual position (cf. Section 3), which resulted in the subject adapting to the rotational motion in the VE by moving forward on a circular path in the real world. The travel distance in the virtual scene, i.e., the arc length of the circular path in the real world, was 3m in all trials. The virtual camera rotation was adapted to different circle radii in the real world. We mapped subjects' virtual translations on circular paths in the real world with radii of 5m, 10m, 20m and 30m. The movement direction in the real world was randomized and counterbalanced for clockwise and counterclockwise progression along the circular paths. We randomized the circle radii over all trials, and tested each 4 times to the left and right. In total, each subject performed 32 curvature trials when walking, as well as when driving with the wheelchair.

For each trial, after a subject performed the movement in the VE, the subject had to decide whether the subject moved on a circular path to the left (left button) or right (right button) in the real world with the Wii Remote controller. After the subject judged the previous motion, subjects were guided to the start position in the real world for the next trial via two 2D markers on a uniform background. The next trial started immediately once the subject assumed the start position and orientation. The procedure was identical for walking, and driving with the wheelchair. To control movements with the wheelchair during the trials, subjects used the joystick to move along the manipulated direction of travel. The physical traveling speed with the wheelchair approximated the mean walking speed of 2.7 km/h.

For the experiment, we slightly modified the joystick control of the wheelchair. An evaluation of the joystick controller showed that the $360°$ motion range of the joystick assumed a slightly elliptical shape, which provided a haptic indication of when the joystick was pushed straight forward, or slightly to the left or right. To reduce the haptic cues that subjects received from the joystick about straightforward motions of the wheelchair in the real world, we placed a circular frame around the joystick handle.

4.4.2 Results

Figure 5 shows the pooled results for the curvature radii 5m, 10m, 20m, and 30m as curvature angle per travel distance $g_C \in \{-\frac{1}{5}, -\frac{1}{10}, -\frac{1}{20}, -\frac{1}{30}, \frac{1}{30}, \frac{1}{20}, \frac{1}{10}, \frac{1}{5}\}$ on the x-axis, with negative values referring to physical paths bent to the left, positive values referring to paths bent to the right, and the standard error over all subjects. The y-axis shows the probability for estimating the real movement as bent to the left while walking straight in the VE. The black psychometric function shows the results for walking subjects, and the gray function for subjects traveling with the wheelchair. We observed a chi-square goodness of fit of the psychometric function of $\chi^2 = 0.2227$ for walking, and $\chi^2 = 0.2191$ for the wheelchair. From the psychometric functions we determined PSEs at a radius of 461.7m for walking, and a radius of 246.6m for driving with the wheelchair, i.e., the responses indicate that subjects on average judged straight movements in the real world as straight. We did not observe a significant difference between
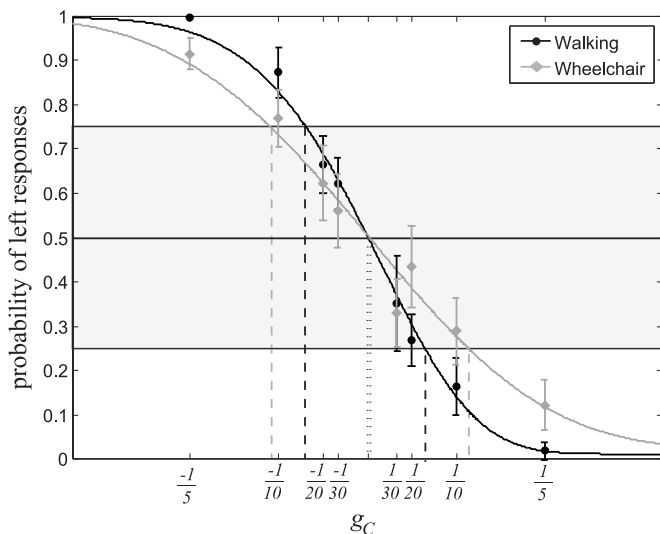

Fig. 5. Pooled results of curvatures while walking (black function), and driving in the wheelchair (gray function). The x-axis shows the g_C gains defined as inverse circular path radius in the real world, with negative gains referring to paths bent to the left, and positive gains to rightward paths. The y-axis shows the probability of estimating the physical movement path as bent to the left.

curvatures to the left and right. A practically applicable range of manipulations is given by the detection thresholds, which we determined from the psychometric functions as radii larger or equal to 14.92m for walking, and 8.97m for driving with the electric wheelchair.

4.4.3 Discussion

The results show a significant impact of the circular path radius on responses. The results show that the walking subjects were less accurate at detecting manipulations of physical walking directions than found in a similar experiment by Steinicke et al. [27]. In particular, our data suggests that the 75% detection threshold may be reached at a circular path radius of 14.92m, whereas the previous results suggested a radius of 22.03m. The differences may be due to the different VR setups, or subject groups, which have been suggested as potential factors [23]. For driving subjects the results show that the detection threshold is reached at a radius of 8.97m, which is surprisingly small compared to the walking condition, suggesting that subjects can be reoriented more when driving with the wheelchair than when walking.

The difference between walking and driving may be caused by different cues provided while moving, and may be influenced by the active locomotor control. In particular, subjects received audiovisual feedback about a straightforward motion in the VE in all trials, as well as angular motion cues about the path curvature, when applied scene rotations became consciously detectable for the subject. From the real world, subjects in both conditions received vestibular and proprioceptive feedback about the curvature radius of the movement path in the real world, which has been found in previous studies to be linked to human locomotor control when walking, i.e., the locomotor state of the body may be adapted according to self-motion percepts [20, 23]. Conversely, the movement direction in the wheelchair condition was controlled by subjects using the joystick. While driving, subjects pushed the joystick all the way forward, and adjusted the joystick to the left or right for virtual straight driving, i.e., subjects received different feedback from the state of their hand depending on the curvature in the real world. As a result, in contrast to experiments E1 and E2, in this experiment the proprioceptive cues from the hand were not independent of the manipulation. However, visual information of the hand and joystick were blocked due to the HMD, such that due to the modified controller there were no direct cues indicating which direction of the joystick corresponds to straightforward motion (see Section 4.4.1).
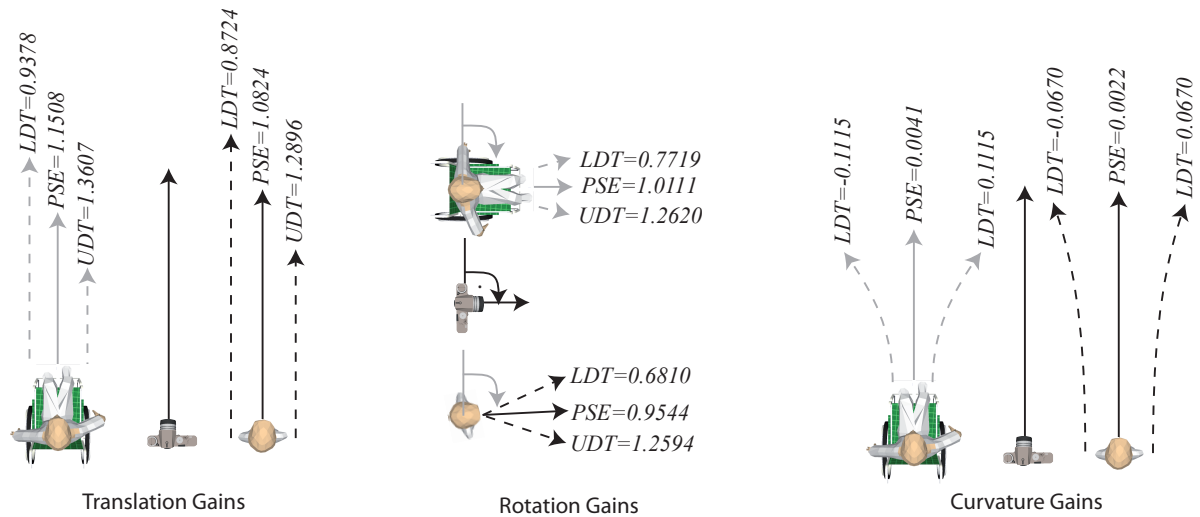
Fig. 6. Illustration of lower and upper detection thresholds (i. e., LDT and UDT) and PSEs for the two physical locomotion means for (left) translations, (center) rotations and (right) curvatures. The wheelchair and walking illustrations indicate relative differences in physical motions to a virtual camera translation or rotation.

4.5 General Discussion

The results of the three experiments suggest that detectability of virtual motion manipulations depends on the physical locomotion method. In particular, subjects driving the electric wheelchair could be redirected more in experiment E3 than subjects walking in the laboratory, which suggests that hypothesis H1 (see Section 3) holds for such manipulations. However, we did not observe comparatively larger detection thresholds for manipulations in experiments E1 and E2. The results indicate that discrimination performance of real and virtual rotations and translations is similar for subjects receiving different cues while walking and driving in the wheelchair.

Moreover, the results indicate differences in the PSEs for rotations and translations between the two conditions. While rotations with the wheelchair showed no significant bias for over- or underestimation of virtual motions, in-place rotations of standing subjects showed a slight overestimation of virtual rotations, which is in line with results of previous studies that evaluated real walking interfaces [27]. Comparing real and virtual travel distances, the results showed an overestimation of virtual translations in both walking and driving conditions, while subjects driving the wheelchair judged virtual traveling to be comparatively smaller than in the real walking condition. The results indicate that virtual translations may have to be upscaled in the wheelchair condition to provide subjects with a visual stimulus of self-motion that they estimate as equal to their physical movements in the real world.

From the debriefing sessions we gathered informal comments on the experiments. Multiple subjects reported that they had difficulties estimating their actual motions in the real world when driving the wheelchair, which indicates that fewer reliable cues from physical movements could be used for the discrimination task. Compared to that, some subjects commented that the wheelchair condition induced a different cognitive context when traveling in the VE, with the impression of having to go faster with the vehicle.

From the results of the Kennedy-Lane pre- and post-questionnaires we determined an average increase of simulator sickness of 6.46 (SD = 2.72) in the walking condition, and 5.78 (SD = 2.07) in the wheelchair condition. We performed a one-way repeated measures analysis of variance (ANOVA), testing the within-subjects effects of the locomotion technique, i.e., walking and driving, on the SSQ scores. We could not find any significant main effects for the SSQ scores ($F(1,22)=1.299$, $p>0.05$), i.e., we did not find any evidence that driving with the wheelchair contributes to or reduces simulator sickness symptoms. The SSQ scores approximate results of previously conducted studies involving walking in HMD environments over the time of the experiment.

The results of the presence questionnaire showed SUS mean scores of 4.82 (SD = 0.91) for walking, and 4.71 (SD = 1.01) for driving with the wheelchair. Again, we could not find a significant difference between walking and driving (ANOVA, $F(1,22)=0.080$, $p>0.05$), which supports the notion that the wheelchair traveling interface can induce a similar sense of presence in subjects as walking.

Furthermore, after the walking and wheelchair conditions we asked subjects to judge their fear of colliding with a wall or physical obstacle in the laboratory during the experiment. The subjects judged their level of fear on a 5-point Likert-scale, with 0 corresponding to no fear, and 4 corresponding to a high level of fear. The results show an average level of fear of 1.17 (SD = 1.53) for walking, and 1.33 (SD = 1.56) for the wheelchair interface, which shows that subjects felt quite safe in both conditions of the experiment. We could not find a significant difference of the reported level of fear between the conditions (ANOVA, $F(1,22)=0.070$, $p>0.05$). On similar 5-point Likert-scales all subjects judged that they received negligible audiovisual position or orientation cues from the real world during the trials in both conditions.

5 CONCLUSION

In this article we have proposed, discussed and evaluated *redirected walking-and-driving*, which denotes the locomotion user interface approach to combine redirected walking in focus regions with redirected driving to cover longer distances in virtual scenes. Both approaches provide users with near-natural vestibular and proprioceptive feedback from actually moving in the real world. The user interface can easily be implemented in head-tracked VR laboratories without extensive hard- and software requirements.

We have evaluated and compared redirection techniques for walking and driving of an electric wheelchair in psychophysical experiments. The results are promising for developers of VR user interfaces (see Figure 6). In particular, the results suggest that subjects can be redirected on smaller circles in the laboratory when driving with the wheelchair compared to when walking (see Section 4.4), and subjects have a tendency to regard upscaled virtual travel distances as matching smaller physical distances when driving the wheelchair (see Section 4.3). Both results suggest that driving may be better suited for longer-distance travel in immersive VEs than real walking.

It remains an open question how different steering interfaces may affect detectability of manipulations. While joystick control of the electric wheelchair provided no direct cues for estimation of physical rotations and translations as discussed in Sections 4.2.3 and 4.3.3, steering with the joystick interface may have provided additional cues when judging physical path curvatures (cf. Section 4.4.3). In the future

we plan to remove those cues entirely, e. g., by adapting the joystick controller for remote input in the laboratory. Compared to traditional redirected walking, which suffers from the problem that changes of a user's walking path can only be induced indirectly with potential for failure cases, we believe that redirected driving can be implemented without such failure cases, and with less detectable manipulations than for walking. Evaluating joystick control compared to other steering controllers may provide more insight into reliability of physical cues when using such steering interfaces. Moreover, we will further evaluate perceptual and cognitive effects of combining natural locomotion techniques for navigation in VEs, with particular focus on disorientation and mental map buildup in unknown virtual scenes, which may benefit from multisensory self-motion cues derived from actually moving in the real world, but may also be affected by integration of manipulated cues in redirected walking or driving environments.

ACKNOWLEDGMENTS

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