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Towards Enabling More Effective Locomotion in VR Using a Wheelchair-based Motion Platform

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Abstract

This paper addresses two questions relevant to the design of effective locomotion methods for VR using a novel wheelchair motion simulation interface. First, we investigate the extent to which people's ability to keep track of where they are in an immersive virtual environment can be facilitated by actual physical movement (rotation and translation) in the context of vehicular travel. Second, we quantitatively analyze various characteristics of the travel paths produced by different types of locomotion control systems to gain insight into the aspects of control that can evoke or impede natural patterns of movement through a virtual environment.

In a within-subjects experiment, we asked 35 volunteers to virtually search through 16 identical-looking boxes randomly placed within a realistically rendered, circularly symmetric virtual room to find 8 hidden targets. Participants performed this task under four different conditions of integrated visual and physical movement, controlled via a joystick interface attached to a motorized wheelchair. In all four cases participants 'drove' their virtual viewpoint using the joystick, but the nature of the accompanying physical movement varied between the conditions. The four conditions were: no physical movement; full physical rotation only; full physical translation and rotation; and "partial" physical translation and rotation, wherein the extent of the actual physical movement was proportionally reduced relative to the visually-indicated movement.

Analysis of the search results did not find a statistically significant main effect of the physical movement condition on total distance traveled or total number of revisits to previously searched locations. However we did see a trend towards greater search accuracy in the full physical motion condition, with a greater proportion of perfect trials, a smaller proportion of failed searches, fewer boxes revisited on average, and more novel boxes searched before the first revisit in that condition than in the others. Analyzing the paths traveled, we found that the velocity and curvature profiles of the virtual motion paths enabled by our novel joystick-controlled wheelchair motion simulation interface were more qualitatively similar to those produced by natural walking than were travel paths we had previously observed when more basic joystick locomotion control methods were used. This suggests potential benefits in adopting a vehicle-simulation movement control method for joystick locomotion control in VR.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Methodology & Techniques]: Interaction techniques.

1. Introduction

It has often been observed that people have a harder time keeping track of where they are when exploring an immersive virtual environment (IVE) than they do in the real world [e.g. WBK*96]. Although these difficulties can be mitigated when a direct real walking interface is used, challenges arise when the virtual environment is larger in extent than the available tracked space.

A variety of approaches have been explored for facilitating spatial understanding in VR when the options for free physical movement are limited. In this paper, we address this problem in the context of a novel locomotion interface achieved using a motorized wheelchair. Akin to a motion simulator but much more economical, this platform has the potential to provide strong vestibular cues to both rotational and translational movement while retaining precise programmatic control over the nature and extent of the actual physical motion that occurs at any given time. Specifically, we present the results of a study that seeks to elucidate the extent to which spatial understanding in VR can be facilitated when visually-indicated translational as well as rotational movements are felt as well as seen.

2. Related Work

2.1. Spatial Cognition

When considering spatial understanding, researchers use several different terms to classify different aspects of space [Mon09]. *Vista space* refers to an area that can be seen all at once from a given vantage point. *Environmental space* refers to an area that requires significant locomotion to explore in full, such as a neighborhood or campus. *Geographical spaces* are those that are too large to be apprehended through direct experience [Mon09]. Current research in spatial cognition [RW06, Wan12] casts doubt on the notion that, during real world travel through environmental space, people actually incrementally construct a global, allocentric, metrically accurate Euclidean cognitive map of their surrounding environment. Converging evidence suggests, instead, that when navigating in environmental space people rely on multiple, local, egocentric encodings of vista space that are interconnected in a topological graph structure [Mel08, EW09]. In this paper we focus on the question of enabling improved spatial understanding in virtual environments within vista space.

2.2. Spatial Updating

As we move about through a large, open environment in the real world, we keep track of where we are with respect to where we have been through a process called *spatial updating*. Under typical conditions, this process is both automatic and obligatory. For example, if people are asked to close their eyes and quickly point to the locations of learned fixed landmarks in a static surrounding environment, their performance does not decline if they are required to physically turn before responding; however they have difficulty responding, after turning, as if they were still facing in the original direction [RvB04]. Also, people find it

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easier to point to the locations of learned landmarks after imagining that they have turned within a stationary external environment than after imagining that the external environment has turned around them [WCP04]. When we use a technologically-mediated locomotion interface to enable the virtual exploration of large remote places, however, the natural process of spatial updating can be disrupted.

In seeking to understand how to best support the spatial updating process in conditions where natural walking is not possible, it is useful to briefly review what is known from previous work. Much research has been done in the field of psychology to elucidate both the cognitive processes involved in spatial updating and the perceptual mechanisms that trigger it [e.g. Rie89, etc.]. We focus here on work that seeks to explore the impact of cues derived from physical (as opposed to purely visual or imagined) movement.

There is strong evidence that some of the various cues (proprioceptive / vestibular / efference copy) provided by real physical movement can play a valuable role in facilitating the process of spatial updating and enhancing spatial understanding. [KLB*98] tested participants' ability to update their heading after travelling along a 2-segment path that contained an intermediate turn. Of the five stimulus conditions: real walking while blindfolded, imagined walking from a verbal description, imagined walking from watching someone else walk, optic flow only, and optic flow with a passive physical turn, they found that performance on a point-to-origin task was significantly better in the walk and passive turn cases than in the other three. Likewise, [LKG11] found that people's performance on a triangle completion task was enhanced when they were passively moved. [CGB*98] found that participants performed significantly more accurately on a point-to-unseen-target task after exploring a virtual environment using real walking than when using a joystick to control their motion virtually. They found that performance was intermediate in a condition that involved real turns but used the joystick to translate. [ZLB*04] similarly found that real walking enabled improved performance on a variety of spatial cognition tasks compared with the use of visual-only and rotation-only virtual locomotion methods. Also, [RL09] found that participants who used a real walking interface performed better on several measures of performance in a hidden target search task than did participants who used a visual-only or rotation-only method.

However, in contrast to the findings of [KLB*98], [SMF*12] found that when people were asked to point to their starting location after virtually traversing a curved path in a highly detailed and realistically-rendered virtual environment, their performance was not improved when they were also passively turned. In contrast to the findings of [ZLB*04], [SFR*10] found no significant difference in participants' performance on a variety of measures of spatial memory and cognition after exploring a photorealistically rendered virtual branching maze using real walking versus gaze-directed virtual travel. Also, [RBM*10] found that performance on 6 of 8 dependent measures in a hidden target search task was equivalent when participants used a joystick-based virtual locomotion method with real turns as when they used real walking. And, [RFR*12] demonstrated that in the absence of visual cues, participants performed as well on a spatial updating task when they experienced the *illusion* of rotational motion as when they actually turned.

Most investigations of the impact of physical motion on spatial updating have focused on the rotational component of the movement. In tests of spatial updating after an imagined change in vantage point, [Rie89] found a significant increase in errors and latencies when the change involved a rotation, but not when it involved a translation, suggesting that the rotational component of physical motion is more important to the spatial updating process than the translational component is. However, [RVB11] found that participants who explored a large virtual environment were able to more accurately estimate distances between landmarks when a linear treadmill locomotion interface was used in conjunction with virtually-executed turns, while allowing real turns in conjunction with virtual translational movement did not offer similar benefits.

In light of these disparate findings, it is clear that more work is needed to fully elucidate the importance and impact of different types of physical motion cues, including translation in particular, as highlighted by [Rud13], to the spatial updating process.

2.3. Redirection

A range of different methods have been developed to allow people to use physical actions within a confined real space to control their virtual travel over unbounded distances in IVEs. Many such interfaces seek to evoke physical sensations related to walking, which may increase the subjective realism of the locomotion experience. Examples of the different types of approaches include: hardware-based solutions such as the omni-directional treadmill [SRS*08]; gesture-based solutions such as walking-in-place [TDS99]; and software-based solutions such as redirected walking [RKW01]. The approach considered in this paper falls most closely into the category of motion simulation platforms [TNB*07], albeit at a very low level of sophistication.

Redirected walking, introduced by [RKW01], seeks to allow the illusion of unbounded free walking in an immersive virtual environment while physically walking within a finite real space. It works by introducing subtle dissociations between the user's actual movement and the associated change in their viewpoint in the virtual environment. Through small, carefully orchestrated manipulations of the visual input, the user is prompted to make small 'corrective' adjustments in the direction of their heading [SBS*12], by which means it becomes (theoretically) possible to keep them walking in circles and never actually reaching the boundaries of the tracked area. In practice, however, 'failure' situations do occur, in which the user finds himself in a state where he cannot move forward. Considerable effort has gone into the development of methods to assuage the cognitive disruption and spatial disorientation associated with such events [PFW10, WNR*07]. [SBJ*10] have determined thresholds for the detection of different types of redirection during real walking, including rotational and translational gains. They found that one would need a lab space of over 40m x 40m to imperceptibly guide people on a curved path of infinite length. However, [HBW11] found that even suprathreshold amounts of rotational redirection do not cause significant spatial interference. [PFW11] found that people performed better on several navigational measures when exploring a large VE using redirected walking with distractor-based re-orientation rather than walking-in-place, or using a joystick to translate.

Redirection implicitly requires the introduction of some visual/vestibular and visual/proprioceptive conflict. Even when such conflict is not overtly noticed, it can still have an impact on peoples' perception of their motion. [CB12] provide a comprehensive review of recent work in multi-sensory self-motion perception under conditions of cue conflict. They report that people's responses generally reflect a combination of the information available from all sources, though body-based cues tend to be given more weight than visual cues when subjects are walking. Studies have so far not shown large differences in peoples' sensitivity to redirection when driving in a motorized wheelchair vs. walking [BIP*12]. Nevertheless, as the distances that people want to traverse in a virtual environment get increasingly large, we believe that driving may become an attractive complement to walking. We know of few studies that have explicitly compared the effect of active locomotion mode (e.g. walking versus biking or driving) on the accuracy of the spatial understanding that people tend to accrue through the active exploration of large, environmental space areas.

While motorized wheelchair travel engages the proprioceptive system to a much lesser extent than do non-motorized travel modes such as walking or cycling, it affords strong vestibular cues to motion. The commercial success of motion simulators attests to some of the benefits that might be expected from such feedback [KP03]. Active wheelchair driving also engages similar cognitive processes as other types of active locomotion. Furthermore, hardware-assisted redirection methods also afford the potential to manage reorientation in a less overtly intrusive manner. Traditional approaches to redirection require the user to subconsciously adjust his physical actions in accordance with the altered visual feedback he receives in order to maintain his locomotor objectives. With redirected driving, we have the ability to provide the user with kinaesthetic feedback that is consistent with his visual stimulus as redirection is being applied [FBI*12]. Furthermore, with redirected driving we have the potential ability to automatically execute evasive maneuvers – such as an exaggerated turn of the chair – when required to avoid a failure state. This could avoid the cognitive disruption associated with having to explicitly notify the user of the need to stop and take corrective action.

2.4. Cybersickness

Redirection involves deliberately introducing variable amounts of sensory conflict between the body-based sensations associated with a person's actual motion (or lack of motion) and their concomitant visual stimulus. It is well-known that noticeable levels of visual/vestibular conflict can lead to cybersickness [Rea78], even if they are infrequent and transient [Dra98]. Such conflict arises when visual motion is immersively experienced in the absence of physical motion, or when there is even a small amount of latency between the onset of visual and vestibular cues to motion. However, cybersickness is less frequently associated with the introduction of a moderate gain in the magnitude of concurrently experienced visual and physical rotational or translational movements. Also, it has been reported that higher levels of proprioceptive engagement are associated with decreased severity of cybersickness symptoms [SH98]. Individuals have been found to vary widely in their propensity to become cybersick, and studies have identified a variety of factors such as gender, age, and prior experience in cybersickness-inducing situations that can co-vary with susceptibility [Kol95].

2.5. Prior Related Experiments

The experiments we report in this paper seek to inform the development of more effective locomotion interfaces for the active, free exploration of large immersive virtual environments by investigating the extent to which spatial understanding can be enhanced when high fidelity visual feedback is augmented with relevant physical cues from rotational and translational motion. In particular, we seek to complement the previous literature [RL06, RL09, RBM*10] by assessing the value of supplementing visual indications of motion with real, *non-walking* physical rotational and translational movement during the exploration of large virtual environments in the context of a motorized wheelchair interface. Our experiments are modelled after the work of [RBM*10], and extend the earlier investigations of [NRI12] through the use of a locomotion interface that allows the integrated control of both real and virtual rotational and translational movement.

[NRI12] compared performance on a hidden target search task under the four conditions of: natural walking, ordinary wheelchair driving, and either sitting or standing and using real turns to rotate but using a joystick to translate. In that work, a trend towards better performance was found in the case of natural walking than in either of the joystick conditions, with intermediate results when the wheelchair was used. However, our ability to interpret the implications of the performance differences between the wheelchair and joystick conditions is complicated by the variations in the mechanism of the locomotor control in those two cases. Specifically, when sitting and using one's feet to turn while using a joystick to move forward, control over the rotational and translational components of motion, which is tightly integrated during walking and wheelchair driving, becomes dissociated. This dissociation could potentially lead to greater cognitive load and less natural movement through the virtual environment, with negative consequences to the spatial updating process. At the same time, physically turning by using one's feet provides a different set of body-based cues to rotational motion than are received when the rotational movement is mechanically controlled – in particular, the proprioceptive system is more extensively engaged, with likely consequent impact on the efference copy. In our current experiment, as will be explained below, these potential confounds are circumvented, and we are able to exclusively focus on assessing the extent to which the spatial understanding of vista-spaces in immersive virtual environments might benefit from the use of a locomotion interface that allows actively controlled, visually-presented motion to be complemented with either fully congruent or dampened but directionally-consistent, passively sensed cues to physical rotational and/or translational motion.

3. The Wheelchair Motion Platform

For the studies reported in this paper, we developed a novel locomotion control system in which virtual changes in viewpoint, actively controlled by a joystick interface and presented via a head-mounted display, can be seamlessly accompanied by either fully- or partially-corresponding physical movement while the user is seated in a computer-controlled power wheelchair.

Our hardware platform was constructed by augmenting a Hoveround MPV5 electric motorized wheelchair with an Arduino microcontroller board. The microcontroller intercepts the voltages output by the wheelchair's joystick and sends them to the computer running the IVE simulation, where they can be modified and returned before they are passed on to the wheelchair's motor controllers. Thus we are able to define the participant's virtual viewpoint based on the raw joystick signals while retaining independent control over the corresponding physical movement of the wheelchair. This gives us the ability to redirect the wheelchair's motion while allowing the user to retain the illusion that they are controlling the wheelchair directly. Details about the microcontroller installation can be found in [FBI*12].

For our present studies, in contrast to the studies by [NRI12], we used this wheelchair motion simulator to control the location of the viewpoint based on the output of the joystick controls. Our goal was to preserve the visual illusion of wheelchair driving while dampening or eliminating various components of the physical movement of the chair. We defined the simulation model by measuring the wheelchair's maximum speed and rate of acceleration from a complete stop for several positional settings of the joystick, considering both linear and rotational motions. This calibration produced a piece-wise linear mapping from joystick inputs to acceleration and top speed in both the linear, y-axis input, case, and in the rotational, x-axis input, case. At each frame, we can then compute the expected wheelchair linear speed and rotational speed based on the calibration data and the current joystick position. Given a joystick x and y, the calibrated values for maximum speed, s_m, and maximum acceleration, a_m, are found from the piecewise linear curve for both linear and rotational velocities. Given these values and the current speed s_i, the next speed, s_{i+1}, is computed as follows:

$$s_{i+1} = \begin{cases} \max(s_m, s_i + a_m \cdot dt) & \text{if } s_m > s_i \\ \min(s_m, s_i + a_d \cdot dt) & \text{otherwise} \end{cases}$$

where dt is the time since the last frame and a_d is a constant deceleration speed, which for this simulation was set to –1 m/sec. The movement of the viewpoint is then updated based on these quantities.

4. Our Experiment

The principal goal of our experiment was to investigate the extent to which passively-experienced physical cues to translational and rotational motion might facilitate people's ability to keep track of where they have been in a richly detailed but landmark-free, vista-space virtual environment. Following [RL06, RL09, RBM*10, NRI12] we used a hidden target search task in a realistically-rendered immersive virtual environment to assess spatial awareness under four different active locomotion conditions, each of which used the same joystick interface to control the virtual viewpoint. Specifically, the conditions differed only in the nature of the physical feedback that accompanied the visually-indicated movement. All participants experienced all conditions, in counter-balanced order. In condition **V** (visual only) the wheelchair did not physically move; in condition **R** (rotation only), the wheelchair was allowed to rotate, but not to translate; in condition **P** (partial) the rotational and translational displacement of the chair was dampened to approximately half that of the visually-indicated movement; and in condition **T** (full) the physical movement of the chair matched its visually-indicated movement. In all cases, subjects were head-tracked and could freely look around in the virtual environment while driving through it.

4.1. Participants

We collected data from a total of 35 participants (26 male, 9 female; aged 18-55, μ = 24.6 ± 8.8), recruited from personal contacts and from passersby to the building housing our lab, and including three of the authors. Two participants were unable to complete the experiment due to technical difficulties with the equipment, and another 13 participants were unable to complete trials in all of the locomotion methods due to cybersickness. The 20 participants who completed all trials were 16 male, 4 female, aged 18-51, μ = 23.2 ± 7.1. The four tested conditions were presented in counterbalanced order among these 20 participants.

4.2. Materials

Each participant experienced each condition using the same hardware, shown in figure 1. We presented the visual stimulus on an NVIS nVisor SX 60 HMD, which uses twin OLED displays to provide a 1280×1024 image to each eye over a manufacturer-specified 60° diagonal field of view with 100% stereo overlap. The HMD is equipped with foam blinders that restrict peripheral vision; however to guarantee complete immersion during testing we dimmed the room lights and draped a large veil of heavy black felt over the front of the HMD. Participants sat in the motorized wheelchair and used the wheelchair's built-in joystick to control their movement through the virtual environment. We used a HiBall 3100 6DOF optical ceiling tracker to separately determine the position and orientation of the wheelchair and the participant's head. Target selection was accomplished using two different approaches. The first fourteen participants used a third HiBall sensor affixed to a hand-held wand, while the next 21 participants used a wiimote. With three HiBall sensors running simultaneously, each sensor operated at 200-400Hz, but when only two sensors were used the update rate increased to ~600Hz. However, we found that this change had no discernable effect on the end-to-end system latency, which we measured as 53ms in the 3-sensor case using the method described by [Ste08]. During the trials, two experimenters managed the cables attached to the HMD so that they would neither pull on the participant's head nor be run over by the wheelchair. We played an ambient soundtrack of tropical birds and flowing water through the HMD's built-in headphones to mask any subtle auditory cues from the outside world.

Figure 1: *The wheelchair platform.*

The virtual environment was modeled using Google Sketchup as a circularly symmetrical room, 10 feet tall and 24 feet in diameter, matching the height and slightly smaller than the narrowest width of our laboratory. We achieved a realistic appearance by texture mapping the walls, ceiling and floor of the model with excerpts from photographs of our lab space. The experiment was implemented using C++ in the G3D rendering engine, which ran on a Windows XP computer with an Intel Core i7 processor, 6GB of RAM and Nvidia Quadro FX 1500 graphics. We compensated for the pincushion distortion of the HMD when rendering and generated the stereo views using a constant IPD for all participants.

4.3. Procedure

Participants began by filling out a demographics questionnaire and a baseline simulator sickness questionnaire (SSQ) [KLB*93]. They then read printed instructions explaining the task and the use of the equipment. The main experiment consisted of a total of 12 hidden target search trials, split into in 4 separate blocks, one for each locomotion method. The first trial in each block was considered as training and discarded; performance measures on the other two trials were averaged to yield one data point per participant, per measure, in each condition for subsequent analysis. To avoid inadvertently biasing participants' interpretation of the different locomotion methods, we took care to refer to each of them solely by their generic, single letter identifiers and we refrained from providing any descriptive information about any of the them. We counterbalanced the presentation order of the methods between participants, and enforced a 5 minute break after each block of 3 trials, during which time the participant was offered water and cookies and asked to fill out a SSQ. After the last trial, participants completed a short exit survey in addition to the final SSQ. The survey forms were customized for each participant, so that each participant was asked to provide feedback about each locomotion method in the same order as he or she had experienced them.

At the start of each trial, participants found themselves in the center of a realistically rendered, circularly symmetric virtual room containing 16 pillars, each of which held an asymmetrically-shaped box whose largest face was colored white. The pillar positions, box orientations, and target locations were all randomly defined at the start of each trial. For the participants who used a third HiBall sensor, this sensor allowed them to directly control a rigidly tracked virtual hand with which they could search a box by reaching out to touch its white side. Participants who used the wiimote to execute the searches had a very similar user experience. To select a box they had to approach it to within arm's length and turn to face its white side. At that point the box face would turn yellow to indicate its availability to be searched via a button press. Half of the boxes contained targets, and would turn red when searched for the first time; the other half, when selected, would turn blue. After being searched, the face color would return to white. All boxes would appear blue if re-searched, requiring participants to remember which boxes they had already visited. A counter was continuously displayed in the upper corner of the display to indicate the number of targets remaining to be found. The trial ended either when the participant successfully found the last of the hidden targets, or after they had made eight consecutive re-searches of previously searched locations. Participants were not allowed to see the color (red or blue) of the last searched box, so that they would not know if a trial had ended in failure.

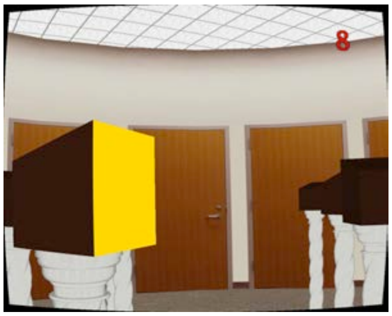

Figure 2: *An example of what participants saw during the experiment.*

Figure 3 illustrates the key differences between the four locomotion methods tested. Each image shows a plan view of the virtual environment with its random boxes. The red paths trace the movement of the virtual viewpoint, while the blue paths show the actual head position. Please note that these images were created for explanatory purposes only, and were made after the completion of the experiment. During testing we did not save the participants' actual head positions for subsequent analysis, just their virtual viewpoint.

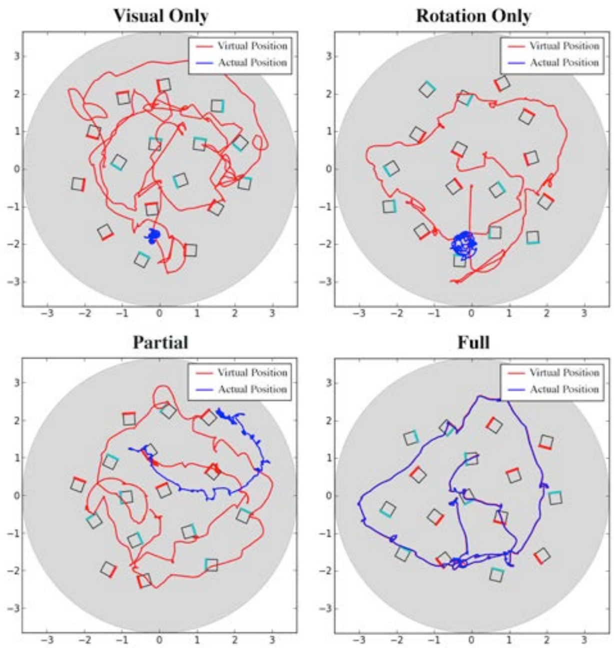

Figure 3: *An illustration of the virtual (red) and actual (blue) head positions during the search task using each method.*

5. Results

A total of 20 participants successfully completed the entire experiment, giving us data from a total of 40 test trials in each of the 4 conditions. Eight of these 20 participants had used the HiBall interface and 12 had used the wiimote to query the box contents. No significant differences due to the selection mechanism were observed. We computed seven performance measures on the pooled data. Figure 4 plots the results of two of these measures: % perfect trials and % failed trials. We can see that there were more perfect searches (with 0 boxes revisited), and fewer failed trials (with 8 consecutive re-searches of previously-searched boxes) in the full motion condition than in the three other conditions. Statistical tests of significance on this data found that $\chi^2(3, N = 160) = 3.53$, $p = 0.32$ for the incidence of perfect trials and $\chi^2(3, N = 160) = 6.25$, $p = 0.10$ for the incidence of failed trials, however, which is not sufficient to reject the null hypothesis.

Figure 5 plots the results of the five other measures: total number of boxes revisited per trial; total distance traveled per trial; number of boxes searched before the first revisit; average distance between successive box searches (a measure of the economy of movement); average speed of movement (total traversed distance/total time taken per trial); and change in cybersickness score between the pre-test and post-test questionnaires for each method. We can see that participants in the full motion condition tended towards having fewer revisits overall, and searching a greater number of novel locations before re-checking a previously searched box, than did participants in the other three conditions. However, an ANOVA analysis found that the only measure on which there was a statistically significant difference in performance between the methods was in participants' self-selected speed of travel during the search task ($F_{3,76} = 11.15$, $p<0.001$). Outliers were not removed before doing the ANOVA.

In the exit surveys of the twenty people who completed the experiment, the majority (7.5) indicated a preference for the partial motion method, followed closely by the full motion

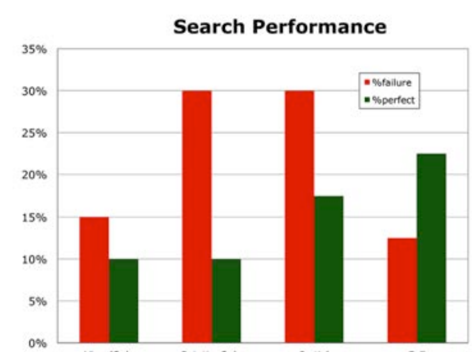

Figure 4: *A plot of the rate of perfect trials (green bars) and failed searches (red bars) in each of the four conditions.*

method (5.5) and visual-only (5). However the majority (9) of the

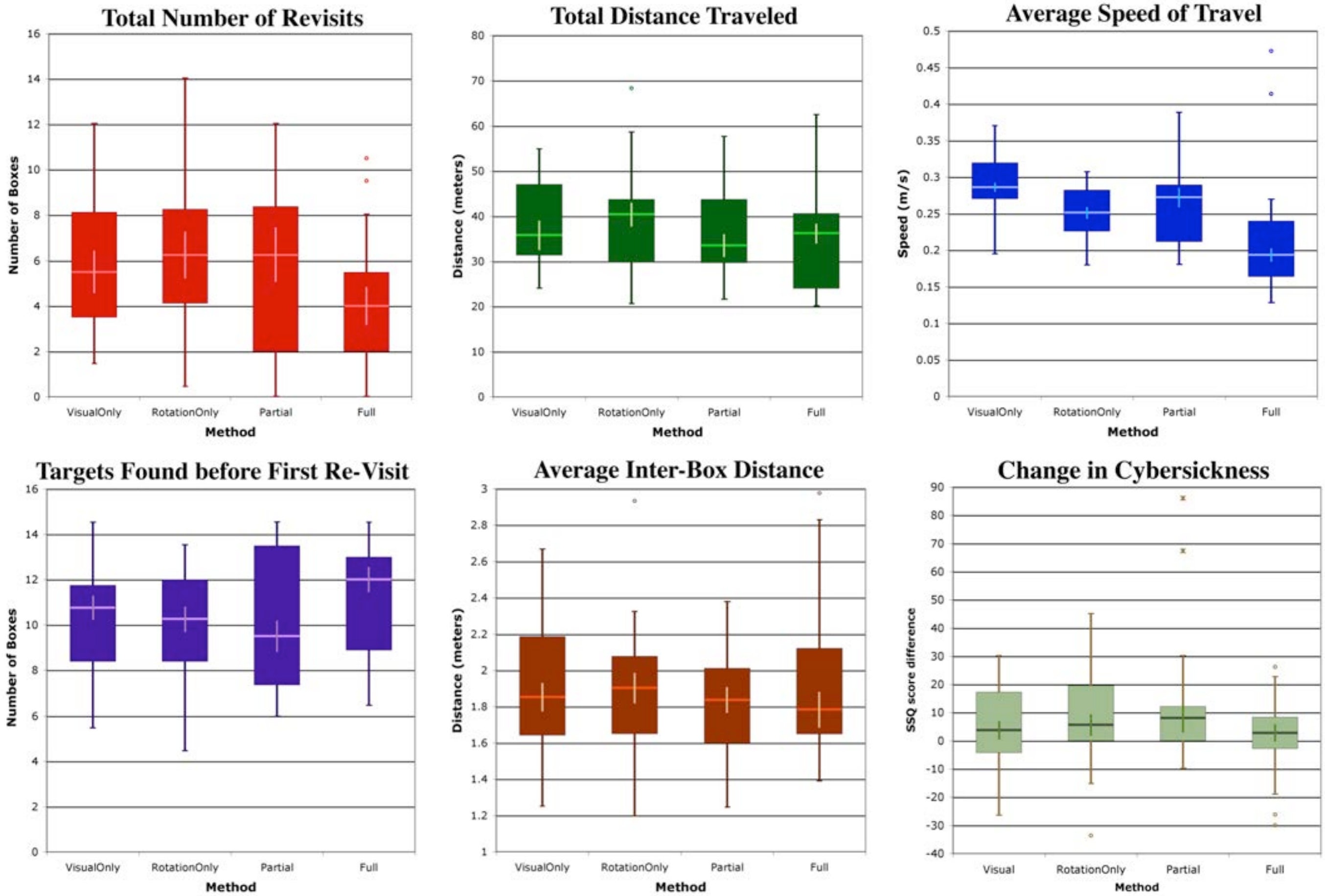

Figure 5: *Box and whiskers plots of several performance measures computed for the 20 participants who successfully completed the experiment. The boxes enclose the range between the 25th to 75th percentile, and the horizontal lines inside the box indicate the median. The whiskers extend from the min to max values within 150% of the inter-quartile range (iqr). Outlying results are indicated by small circles, or by stars if beyond 300% of the iqr. The smaller vertical lines inside each box bound the 95% confidence interval around the mean. Although we can see a slight trend in the revisit data, only the differences in speed were statistically significant.*

13 participants who had to discontinue their participation due to cybersickness fell ill during the partial motion trials, and we did not collect preference data from the participants who did not finish the experiment. Again considering only the 20 participants who completed all trials, ten of them made comments either to the effect that the full-motion method felt too fast or that the partial-motion method felt more realistic. However, eight others made comments to the effect that the full-motion method felt most realistic, and/or less nauseating than the partial-motion method. Two participants did not comment on any notable differences between these two methods. In other feedback, ten participants cited the lack of movement in the visual-only case as a problem, along with complaints of nausea or ease of getting lost. However, six other participants either expressed a preference for the lack of movement in this case, or explicitly said that they did not see it as a problem.

Finally, we noted remarkable similarity in the qualitative nature of the paths traversed between the four locomotion methods examined in this experiment. Comparing histograms of both speed and curvature, following the methods of [RVB13], we found that the characteristics of participants' virtual movement using our wheelchair motion simulator in the visual-only, as well as the **R** and **P** conditions, were qualitatively similar to when the joystick controls were directly driving the wheelchair. This stands in stark contrast to the quality of motion we observed in earlier experiments [NRI12] where participants used the joystick to control their translational movement while physically using their bodies to turn. Figure 6 compares a trace of the 'worst' (maximum distance) path over all trials in our visual_only condition and in the joystick/sitting condition from [NRI12].

6. Discussion

Several factors complicated our ability to compare the four locomotion methods as effectively as we had intended. The first

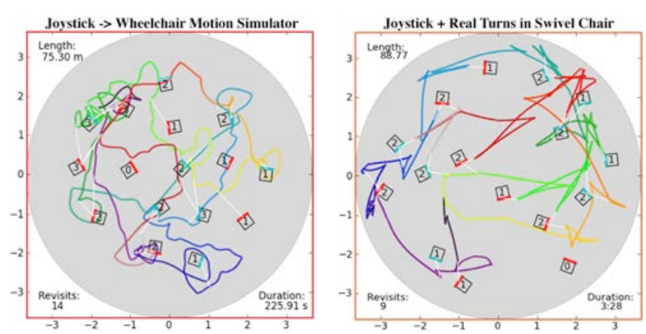

Figure 6: *Left: a trace of the longest traversed path in the Visual_Only (**V**) condition in our present experiment where movements of the joystick controlled a wheelchair motion simulator; Right: a trace of the longest path in an earlier experiment where participants controlled their orientation in a swivel chair with their feet while using the joystick to translate.*

major problem we ran into was with cybersickness. Three of the four locomotion methods we tested (**V**, **R**, and **P**) involved a dissociation between the visual and vestibular feedback that people received, and we knew that with any such dissociation cybersickness could be a concern. We encouraged participants to discontinue the experiment if they felt cybersick, but were surprised when a total of 13 people terminated early for this reason. Nine these 13 discontinued because of sickness in the partial-movement condition and four because of sickness in the rotation-only case. Of the 20 participants who completed all trials, most did not show significant signs of cybersickness, though there were several cases where people had high SSQ scores in one or more conditions but then felt recovered enough after the mandatory break to continue with the other methods.

Extensive diagnostic testing subsequently revealed a shortcoming in the design of our virtual motion simulator that was likely to have been the aggravating factor. Essentially, the model we used did not properly account for the inertial forces acting upon the chair, particularly when it was accelerating from a resting position, and when the alignment of the passive rear wheels was not consistent with the direction of the intended forward motion of the chair. Figure 7 shows a close-in view of the velocities of motion of the chair (green) and the virtual viewpoint (red) in the **P** (dampened movement) condition while the wheelchair was being driven forwards and backwards in a straight line. One can see in this example that the virtual viewpoint is starting to move ahead of the physical movement of the chair (a 'reverse' lag), although the timing of the deceleration is well-matched. The amplitude differences are of course by design, and consistent with our aims.

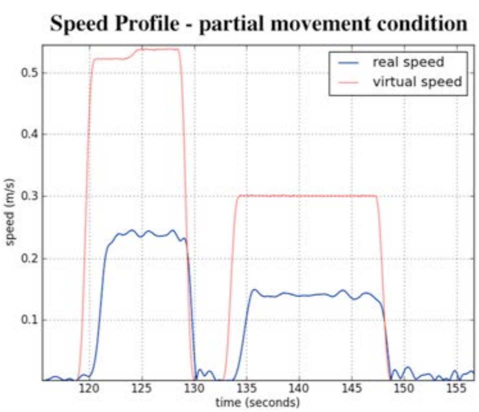

Figure 7: *A plot of the rate of perfect trials (green bars) and failed searches (red bars) in each of the four conditions.*

The second complication we encountered was that in the two conditions that involved substantial physical movement, subjects occasionally ran the wheelchair too close to the walls of the lab, necessitating an adjustment of their physical position. Interruptions also occurred at times due to problems with loose contacts in the cables. Our system log recorded a total of 10 interruptions during the full motion trials and 14 during the partial motion trials, as well as 7 in the rotation-only condition and 1 in the visual-only condition. Post-hoc testing found that two of the performance measures, distance and time, were significantly worse in the interrupted than in the non-interrupted trials, but – probably because the interruptions were relatively broadly distributed – when we re-analyzed the data considering only the uninterrupted trials we found no qualitative difference in the pattern of results.

Despite these shortcomings, we believe that the results of our experiment are able to contribute informative new insights on several key points. First of all, we see a performance trend that supports the idea that people are somewhat better able to keep track of where they are while immersively exploring a visually-detailed but landmark-free vista-space virtual environment when they receive reliable physical feedback in addition to visual feedback about their motion, even when their physical motion is not controlled by walking but rather by sitting passively and driving. This observation extends the results of earlier experiments [RBM*10, RL09, NRI12] and suggests potential benefit in the continued investigation of locomotion control methods that involve actual physical movement as opposed to purely simulated travel. Secondly, our experience provides a cautionary example of the potentially deleterious impact of providing physical motion feedback that is not adequately representative of the concomitantly indicated virtual motion. In the two locomotion conditions where the correspondence between the visually-indicated and physically-felt motions was close in some ways but imperfect in others, a lot of people got sick despite the fact that others were perfectly content. Accompanying a visual signal with conflicting or lagging vestibular cues to motion can cause cybersickness even if such incidences are both sporadic and brief, and the problem may even be worse under these conditions than when no motion cues are provided at all. Thirdly, in this work we have developed a model for locomotion control via joystick movement that evokes more natural traversal behaviours through a virtual environment than we have observed in the past using a simpler and more direct mapping from joystick position to changes in virtual viewpoint. By constraining the joystick to control participants' virtual movement in an identical fashion as it would control the actual movement of a wheelchair, we created affordances that encouraged people to travel in ways that more closely matched the characteristics of the travel paths they naturally chose when walking. Our observations are resonant with the findings of [FHS*06], who observed the importance of providing people with properly-integrated control over both the rotational and translational components of motion in order to facilitate natural engagement and support effective user interaction.

7. Future Work

Going forward, our first order of business is to improve the fidelity of the model that drives our motion control simulator, which will allow us to more robustly explore possibilities associated with providing physical feedback that can better support the illusion of achieving the fluid, free exploration of large immersive virtual environments within restricted real spaces. In addition, we will seek to build on the findings from our present studies to better inform the understanding of the extent to which passively felt, but actively controlled, physical motion feedback may support the spatial updating process and thereby help people to better keep track of where they are while exploring an immersive virtual environment.

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