Do We Need to Walk for Effective Virtual Reality Navigation? Physical Rotations Alone May Suffice.

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Abstract. Physical rotations and translations are the basic constituents of navigation behavior, yet there is mixed evidence about their relative importance for complex navigation in virtual reality (VR). In the present experiment, 24 participants wore head-mounted displays and performed navigational search tasks with rotations/translations controlled by physical motion or joystick. As expected, physical walking showed performance benefits over joystick navigation. Controlling translations via joystick and rotations via physical rotations led to better performance than joystick navigation, and yielded almost comparable performance to actual walking in terms of search efficiency and time. Walking resulted, however, in increased viewpoint changes and shorter navigation paths, suggesting a rotation/translation tradeoff and different navigation strategies. While previous studies have emphasized the importance of full physical motion via walking (Ruddle & Lessels, 2006, 2009), our data suggests that considerable navigation improvements can already be gained by allowing for full-body rotations, without the considerable cost, space, tracking, and safety requirements of free-space walking setups.

1 Introduction

Virtual reality and other multi-media technologies that can create computer-mediated experiences have become more widespread, affordable, and accepted in recent years. In fact, as a large body of fiction literature and cinema have shown, there have been many exaggerated claims about the potential experience virtual reality will ultimately offer – that is, an almost super–human experience that far exceeds real-world possibilities (see, e.g., movies like *The Matrix*). The level of realism and detail of current audio-visual simulations can indeed be stunning. Despite those promising claims and achievements, however, the user experience of virtual reality (VR) does not match its fictional characterization, and there remain a number of major challenges. One of these challenges is spatial orientation. Even though one might hope that VR should ultimately enable us

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to locomote and orient as well as in the real world – or potentially even better, as VR can allow for the physically impossible (e.g., teleporting, flying, bird eye's views, or multiple and even simultaneous perspectives to chose from) – spatial orientation in VR can be quite poor.

1.1 Spatial Orientation in VR

Under certain circumstances VR-users take significantly longer to learn virtual environments than comparable real environments (Richardson, Montello, & Hegarty, 1999; Witmer, Bailey, Knerr, & Parsons, 1996), and often produce large random and systematic errors in virtual environment (VE) navigation (Riecke, 2008). Recent studies have demonstrated that participants in visually-based VR also produce certain novel types of qualitative errors such as left-right confusion or failure to update visually simulated rotations altogether (Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Avraamides, Klatzky, Loomis, & Golledge, 2004; Riecke, 2008). Note that such qualitative errors do not occur in comparable real-world situations where participants are allowed to physically walk the trajectory that was only visually simulated in the VR task (Klatzky et al., 1998). Furthermore, retrieval of memories of a real environment seems to be affected by features of the environment (Riecke & McNamara, 2007) in a way that retrieval of memories of virtual environments is not (Moura & Riecke, 2009; Williams, Narasimham, Westerman, Rieser, & Bodenheimer, 2007). In summary, there seem to be many situations where spatial orientation performance in VR is worse than real-world performance.

There are, however, a few noteworthy exceptions where visual cues presented in immersive VR can be sufficient for spatial orientation tasks: When high visual realism is combined with an abundance of reliable landmarks and an immersive HMD or projection system, visual cues may be sufficient to enable excellent homing performance (Riecke, van Veen, & Bülthoff, 2002) as well as spatial updating performance that approaches real-world performance (Riecke, von der Heyde, & Bülthoff, 2005).

In general, though, performance in VR spatial orientation tasks seems to benefit from physical locomotion in the environment (Avraamides et al., 2004; Chance, Gaunet, Beall, & Loomis, 1998; Klatzky et al., 1998; Pausch, Proffitt, & Williams, 1997; Ruddle & Lessels, 2006; Waller, Beall, & Loomis, 2004; Wraga, Creem-Regehr, & Proffitt, 2004). Especially when participants are asked to respond not only as accurately as possible but also as fast as possible, visual path-integration based spatial orientation in VR often shows strikingly large systematic as well as random errors (Riecke, 2008). In sum, despite impressive advances in VR hardware and software, human spatial orientation is often still far from the real-world-like performance, where automatic spatial updating can allow for intuitive yet effective spatial orientation with minimal cognitive load (Farrell & Robertson, 1998; Klatzky et al., 1998, e.g.,). The current study was designed to elucidate the origins of this difference in human navigation ability between real and virtual environment by assessing the relative contribution and relevance of physical translations and rotations.

1.2 Goal of this study: Investigate relative contribution of physical translations and rotations for effective navigation in VR

Whereas self-motions in VR can be easily visually simulated using affordable off-the-shelf hardware and software, creating a VR system that allows users to physically walk in a natural manner through the simulated world requires considerable cost, effort, and safety measures. Such a system typically requires a sufficiently large obstacle-free space for participants to walk unimpeded, the use of head-mounted displays (HMD), the ability to track the motion of the HMD, and an experimenter present to ensure that the participant does not walk into physical walls, stumble over cables, etc. It is therefore critical to assess if there is sufficient benefit from physical locomotion/walking to justify the high effort and cost associated with large free-space walking – especially given that physical rotations alone can be realized without the need for large tracked free-space walking areas. In this context, a series of studies by Ruddle & Lessels (2006, 2009) is of particular importance and will be discussed here in more detail, as it addresses these issues directly and inspired the experimental paradigm of the current study.

1.3 Navigational Search Studies by Ruddle and Lessels

Ruddle and Lessels performed a series of navigational search studies in which participants were in a real or virtual rectangular room that contained a regular arrangement of 32 pedestals, half of which had closed boxes placed on top (Lessels & Ruddle, 2005; Ruddle & Lessels, 2006, 2009). Participants were asked to search for eight target objects hidden in these 16 boxes.

In a real-world test, participants performed with almost perfect efficiency: participants found all eight targets without any re-visits of boxes in 93% of trials (Lessels & Ruddle, 2005). Even when blinders restricted the field of view to just 20°×16°, performance was not significantly reduced (87% perfect trials without revisits, see Fig. 2). When performing a similar task using an HMD with a FOV of 48°×36° and physical walking, performance was similar (90% trials without revisits), and was independent of whether the visual scene was modeled with high or low visual realism (Ruddle & Lessels, 2006). This suggests that free-space walking with an HMD can allow for performances that matches real-world performance, at least for the task at hand. However, performance was substantially reduced when visually simulated translations were controlled using a button-press interface ("real rotation" condition) instead of physical walking (43% no-revisit trials, see Fig. 2), even though rotations in the VE were still controlled by physical rotations (Ruddle & Lessels, 2006). This suggests that both translational and rotational physical motion cues are required to allow for real-world-like performance in such search tasks.

When the HMD was replaced by a monitor and rotations and translations were controlled by moving a computer mouse and pressing buttons on a keyboards, respectively (Ruddle & Lessels, 2006), performance did not significantly decrease further (45% no-revisit trials in the "visual only" condition, see Fig. 2). One might be tempted to conclude from those data that adding physical rotations did not show any performance benefit (and the authors do, in fact, suggest that). It is possible, however, that the experimental methodologies in (Ruddle & Lessels, 2006, 2009) could have contributed to the observed similarity in performance for the visual-only and real rotation condition:

Whereas Ruddle & Lessels (2006, 2009) used the same display (a stereo HMD with 640 × 480 resolution) for the walking condition and real rotation/keyboard translation condition, a different display device (a 21 inch desktop monitor) was used in the visual only (mouse rotation/keyboard translation) condition. This change in display device produced several differences in the nature of the visual experiences that might have contributed to Ruddle and Lessels's findings. Potential differences include display quality and resolution (presumably higher for monitor); availability of binocular depth cues (HMD only); tracking latency (HMD only); peripheral visibility of surrounding room (monitor only); immersion and presence (higher perhaps with HMD); eye height (sitting for monitor vs. standing for HMD); mismatch between simulated eye height (always 1.65m) and physical eye height (especially in monitor condition); and absolute size of the display (21" for monitor vs. 2 × 1.3" for HMD).

Many of these parameters have been shown to impact human spatial orientation performance (Riecke, Schulte-Pelkum, & Bülthoff, 2005; Riecke et al., 2002; Tan, Gergle, Scupelli, & Pausch, 2006, 2004; Tan, Gergle, Scupelli, & R.Pausch, 2005; Alfano & Michel, 1990). Moreover, Ruddle and colleagues themselves had demonstrated that replacing an HMD with a desk-top monitor reduces navigation performance in VR, indicated by increased navigation times and less accurate sense of straight-line distances (Ruddle, Payne, & Jones, 1999). Hence, any direct comparison between results from the monitor (visual only) condition and the HMD (real rotation and walking) conditions should be treated with caution. The current study was designed to avoid these potential problems by using the same HMD in all conditions, thus allowing for a direct and more trustworthy comparison between all three conditions, and thus a more reliable assessment of the relative importance and contribution of physical translations versus rotations for VR navigation. To this end, we used a similar overall navigational search methodology as Ruddle & Lessels (2006, 2009), with the following major changes:

- **Same Display for all Conditions** The same visual display (HMD) was used in all conditions.
- **Orientating Cues from Environmental Geometry and Rectangular Object Structure Removed** Recently, Kelly, McNamara, Bodenheimer, Carr, & Rieser (2008) showed that navigators can use room geometry to maintain orientation during spatial updating in immersive VR. This suggests that participants in Ruddle & Lessels (2006, 2009) might have used the geometry of the surrounding room as well as the rectangular arrangement and regular orientation of the objects to reorient themselves or maintain global orientation, which might in turn have contributed to the observed lack of any benefit of physical rotations (as visual cues were sufficient for effective (re)orientation). To avoid any influence of environmental geometry or intrinsic reference frame of the object layout, we removed the surrounding room and randomly positioned and oriented all objects for each trial. Furthermore, we refrained from using a naturalistic, landmark-rich environment, as this might have obfuscated potential effects of locomotion mode due to, for example, instantaneous spatial updating or other kinds of powerful visual re-orientation mechanisms (Riecke et al., 2005; Riecke, Cunningham, & Bülthoff, 2007).
- **Joystick as Continuous Input Device** While Ruddle & Lessels (2006, 2009) used a simple button-based translation input paradigm in the visual only and real

rotation condition where participants could not continuously adjust their translational velocity, we used a wireless joystick that allowed for easy and continuous adjustment of translational and rotational velocities.

- **Posture and Eye Height Matched for all Conditions** Participants were always standing, with the simulated eye height matching their actual eye height.
- **Within-Participant Design** As between-participant variability is often strikingly large for spatial orientation tasks (even more so in VR), we used a complete within-participant design for the current study.

2 Methods

Participants Twenty-four adults (19–46 years old, half female) from the Nashville community participated for monetary compensation.

2.1 Stimuli and Apparatus

Virtual Environment Participants wore an HMD that displayed a simple virtual scene that contained a large textured ground plane and 16 identical objects (randomly oriented 3D models of a pedestal with a miniature birdhouse on top). Eight of the 16 birdhouses contained red balls as target objects that participants had to search for, and the remaining eight birdhouses were empty and acted as decoys. The position of the targets objects was randomly Poisson-disk distributed within a circular area of 4m diameter for each trial to avoid orienting cues and learning effects. This size was chosen such that the object layout fitted safely withing the 5×5m free space walking area of the actual lab. As we were interested in investigating different locomotion modes, we did not simulate room geometry or other potential landmarks or regular object layouts that could have been used to guide or re-orient participants (Kelly et al., 2008). In particular, the ground texture and sky contained no orientation cues.

Visualization The virtual scene was presented binocularly through a head-mounted display (NVIS NVisor SX) at a native resolution of 1280×1024 pixel with complete binocular overlap. The simulated field of view (FOV) matched the physical FOV of $60°$ diagonal (corresponding to $48° \times 36°$ or 27 pixel/°).

Tracking and Interaction The HMD was tracked at 60Hz using the WorldViz PPT tracking system. Participants carried a wireless joystick (Logitech Freedom 2.4) that was mounted on a wooden board that was worn using shoulder straps.

Headphones and Ambient Sound Masking To mask spatialized auditory cues that could have been used to reorient in the lab, a broad-frequency river-like sound was displayed via the headphones integrated in the HMD throughout the experiment.

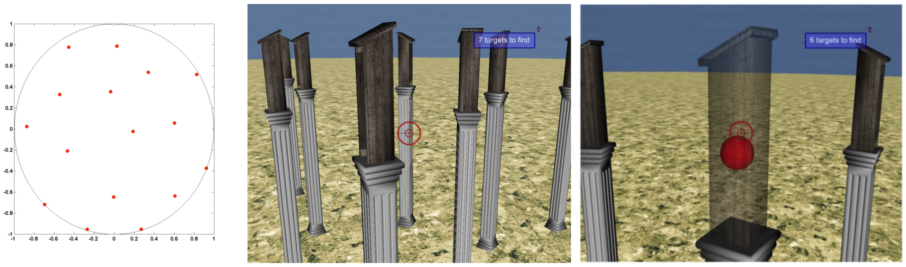

Fig. 1. Left: Sample unit circle Poisson-disk distribution of the pedestal array, which was randomized per trial. These values were scaled by the experimental radius (2m) and represented the positions of the pedestals on the ground plane. **Middle**: Experimental view, with the cross-hair indicating the current motion direction. **Right**: By pressing a designated button on the joystick, participants could look inside a birdhouse for 2 seconds to see if it contained a target object (red ball).

Task Participants' task was to navigate the VE until they had encountered each of the eight targets, using a designated button on the joystick to render the walls of the birdhouses semi-transparent for two seconds. Additional auditory cues indicated upon button-press whether the object was a target or decoy. Birdhouses that had already been visited were populated with blue balls: either a blue ball appeared if the birdhouse was previously empty, or the red ball turned blue upon visitation. If targets were revisited, a different sound was also played and a blue ball was visible. Participants were instructed to minimize the number of re-visits, distance traveled, and time needed without starting to rush or run through the VE. A trial was terminated when either all eight target objects were found or when there were eight consecutive revisits (i.e., looking into previously-visited birdhouses). A message in the upper right hand corner of the screen displayed the current number of targets left to find in a trial.

Locomotion Modes To investigate the relative contribution and importance of physical motion cues for translation and rotation, we employed three different locomotion methods:

In the "**walking**" condition, all six degrees of freedom of the HMD were tracked and participants navigated through the virtual scene by physically walking (translating and turning).

In the "**real rotation**" condition, tracking of physical translations in the horizontal plane was switched off, and participants instead had to use joystick deflections to translate through the virtual scene. Rotations and up-down translations were still controlled by corresponding physical motions.

In the "**joystick**" condition, both horizontal translations and yaw/pitch rotations in the VE were controlled by the joystick deflections and rotations, respectively.

Note that participants were standing in all motion conditions.

Motion Model Joystick deflections were linearly mapped onto translational velocities in the VE ("velocity control" mapping). Yaw rotations were controlled by yaw-rotations of the joystick handle using a velocity control mapping, whereas pitch rotations were controlled using the lever on the side of the joystick using a position control mapping (as that lever did not have a re-centering force). Maximum joystick rotations and deflections resulted in velocities that matched the typical maximum physical motion velocities we observed during pre-tests in the full-motion condition (1m/s and 90°/s). A joystick dead zone was used to enable precise navigation and to ensure that participants were stationary in the VE when they did not touch the joystick.

2.2 Procedure and experimental design

Each participant completed one practice trial and three test trials for each of the three locomotion modes, resulting in a total of twelve trials[4]. Locomotion modes were blocked and balanced across participants. Trials lasted 2min on average, and participants took anywhere between 40s and 4min to complete a given trial. To reduce the likelihood of fatigue and simulator sickness, participants were allowed to take off the HMD and take a short break after each trial. Additional breaks were scheduled after each block of four trials. The pedestal layout and orientation were independently randomized for each trial to prevent layout learning. Participants started each trial at the perimeter of the object array facing inwards. After the experiment, participants were debriefed, payed, and thanked for their participation.

3 Results

Data for the different dependent measures are summarized in Fig. 3 and analyzed using repeated-measures ANOVAs and planned pairwise contrasts for the independent variable locomotion mode (3 levels: walking; real rotation and joystick-based translation; joystick rotation and translation). Statistical results are summarized in Table 1.

Number of Perfect Trials Lower than in Ruddle & Lessels (2006) Study Comparing overall performance between the current study and the study by Ruddle & Lessels (2006) shows two main differences, as illustrated in Fig. 2: Whereas participants in Ruddle & Lessels (2006) were able navigate "perfectly" (i.e., find all targets without any revisits) in 90% of the trials in the HMD walking condition, performance dropped to only 43% and 45% perfect trials in the real rotation and visual only condition, respectively (cf. Fig. 2). In contrast, participants in the current study performed overall considerably worse, irrespective of the motion condition (cf. Fig. 2): Only 13.9% of the trials were finished without any revisits in the walking condition, and performance did not significantly drop further when physical motion cues were excluded for translations (real rotation condition) and rotations (joystick condition) (cf. Table 1).

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[4] Twelve additional trials that used a gain factor of 10:1 between visually simulated and actual translations were excluded due to technical problems with the tracking. These 10:1-gain trials were performed in one session, either before or after the 1:1 gain trials. The order of the 10:1 versus 1:1-gain sessions was balanced to avoid systematic order effects.

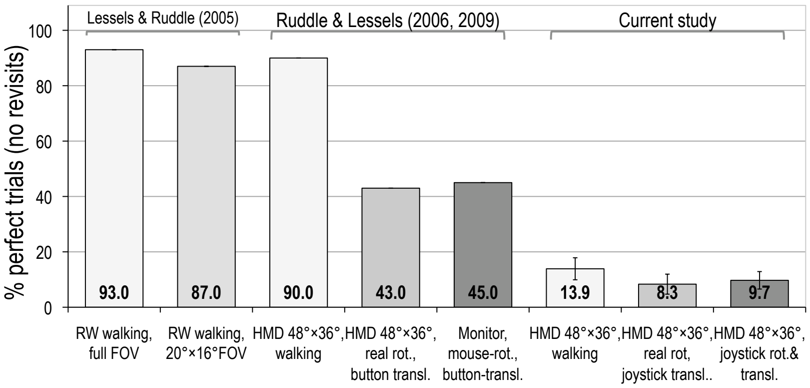

Fig. 2. Re-plotting of the data from Lessels & Ruddle (2005) and Ruddle & Lessels (2006, 2009) for comparison with the current data.

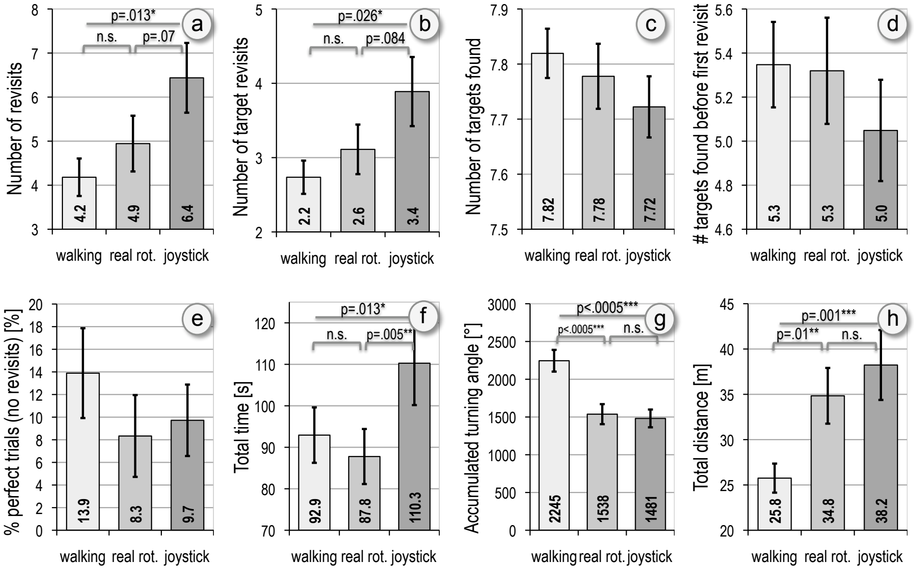

Fig. 3. Mean data for the different dependent measures. Error bars indicate ±1 standard error of the mean.

	ANOVA main effect			Contrast real walking vs. real rotation			Contrast real rotation vs. joystick		
	F(2,46)	p	η_p^2	F(1,23)	p	η_p^2	F(1,23)	p	η_p^2
Number of revisits	**4.803**	**.013***	**.173**	1.211	.282	.050	*3.610*	*.070m*	*.136*
Number of target revisits	**3.858**	**.026***	**.147**	.983	.332	.041	*3.262*	*.084m*	*.124*
Number of targets found	1.060	.355	.044	.282	.601	.012	.885	.357	.037
# targets found before 1st revisit	.608	.511	.026	.007	.934	.000	.637	.433	.027
% perfect trials (no revisits)	.926	.404	.039	1.353	.257	.056	.138	.714	.006
Total time	**4.814**	**.013***	**.173**	.560	.462	.024	**9.430**	**.005****	**.291**
Accumulated turning angle	**25.20**	**<.0005*****	**.523**	**29.47**	**<.0005*****	.562	.491	.490	.021
Total distance traveled	**7.621**	**.001*****	**.249**	**7.843**	**.010****	**.254**	1.130	.299	.047

Table 1. Analysis of variance and planned pairwise contrasts results for the different dependent variables. The asterisks indicate the significance level (α = 5%, 1%, or 0.1%). Marginally significant effects ($\alpha \leq 10\%$) are indicated by an *'m'*. Significant and marginally significant effects are typeset in bold and italics, respectively. The effect strengths partial η_p^2 indicates the percentage of variance explained by a given factor.

Number of Revisits Needed to Complete the Task was Highest for Joystick Condition Whereas participants in the joystick condition revisited on average 6.4 pedestals before completion, being able to walk significantly reduced this number to only 4.2 revisits (cf. Fig. 3a and Table 1). This might be interpreted a participants being less lost in the walking condition. Interestingly, the contrast analysis revealed that replacing walking with joystick translations in the real rotation condition did not significantly impair performance, whereas replacing actual rotations with visually simulated rotations in the joystick condition marginally increased the number of revisits. A similar data pattern was found for the number of targets revisited (Fig. 3b): Whereas the joystick condition yielded significantly more revisits than the walking condition, performance in the real rotation condition equaled the walking condition.

Number of Targets Found did not Depend on Motion Condition Figure 3d shows that participants on average found about five targets before their first unplanned revisit of any pedestal. This measure ("number of targets found before first revisit") could thus be taken as a conservative estimate of when on average participants first got "lost" in the environment and could not tell any more whether they had previously visited a given location or not. The lack of any significant differences between the motion conditions (cf. Table 1) suggest that the availability of physical motion cues in the walking condition did not provide any useful cues that participants could have successfully used to remain oriented and prevent revisits. Note that not all trials were successfully completed (cf. Fig. 3c), as trials were automatically aborted after eight successive revisits to previously-visited pedestals. In the walking condition, an average of 7.82 out of 8 targets were found, and this number did not drop significantly for the real rotation or joystick condition (cf. Table 1).

Navigational Search was Fastest in Walking and Real Rotation Condition Figure 3f shows that participants took overall about 25% longer in the joystick condition, as compared to the real rotation condition where head motions instead of joystick motions were used to control orientation changes in VR. Allowing for actual walking did not reduce navigational search time further, suggesting that physical translations are less critical than physical rotations for search efficiency.

Walking Led to Increased Orienting Motions and Reduced Path Lengths Figure 3h shows that participants covered about 35% less overall distance in the walk condition (25.8m) than in the real rotation condition (34.8m). This decrease in traveled distance for walking was, however, accompanied by a 46% increase in the amount of head rotations (Fig. 3g): Accumulated turning angles significantly increased from 1538° (or 4.27 revolutions) to 2245° (or 6.24 revolutions). This suggests a qualitatively different navigation strategy in the walking condition: By looking around more in the walking condition were participants able to optimize the trajectory, thus traveling less far. Note that this strategy did not, however, reduce the amount of time needed for the navigational search task in the walking condition as compared to the real rotation condition (Fig. 3f). In fact, apart from a reduction in the amount of distance walked, none of the seven other dependent measures shows any significant benefit of physically walking as compared to joystick translations combined with physical rotations.

4 Discussion and Conclusions

In an important series of studies on navigational search in real and virtual environments, Ruddle and Lessels found that participants performed better when allowed to freely walk, as compared to a “real rotation” condition where they wore an HMD and could freely rotate while controlling simulated translations using a button-based motion model (Lessels & Ruddle, 2005; Ruddle & Lessels, 2006, 2009). This real rotation condition led to similar performance as a visual only condition, where both translations and rotations were only visually simulated on a desktop monitor, and controlled via keyboard presses and mouse motions, respectively.

These data led Ruddle & Lessels (2006) to posit that full physical movement is essential for effective navigation in VR, whereas physical rotations alone are insufficient. The current study replicated the overall navigational search procedure of Ruddle & Lessels (2006) while controlling for a number of variables that could have affected the previous results and interpretations (see discussion in the introduction section). Most importantly, we used the same display device (HMD) for all motion conditions, and carefully removed salient landmarks and other potential visual orienting cues by removing the rectangular room environment and randomly positioning and orienting all objects in the scene for each trial. Note that these changes were expected to increase overall task difficulty. Furthermore, we used a joystick-based motion paradigm that allowed for smooth, continuous and intuitive adjustment of rotational and translational velocities instead of the button- and mouse-based motion model used in (Ruddle & Lessels, 2006, 2009). Controlling for these variables in the current study led to a qualitatively different pattern of results.

Whereas there was still an overall benefit for full physical motion (walking condition) as compared to joystick navigation, merely allowing for bodily rotations (real rotation condition) provided considerable performance benefits when compared to the joystick (visual only) condition. Moreover, real rotation performance almost equalled walking performance: Only one of the eight dependent measures (total distance traveled) showed a clear and significant benefit of walking over real rotation. In fact, participants in the walking condition of our study seemed to trade off distance for rotations, insofar as they walked less but turned more, which might be caused by a shift in navigation strategy.

In sum, comparing previous results by Ruddle & Lessels (2006, 2009) with our results raises several major questions that we will discuss in the following subsections.

Did the Lack of Orienting Cues in our Study Cause the Performance Drop Compared to Ruddle & Lessels (2006, 2009)? As the overall navigational search paradigm was quite similar in the current study and (Ruddle & Lessels, 2006, 2009) (especially for the walking condition), we propose that the large overall performance decrement in the current study might be caused by differences in environmental geometry and the intrinsic geometric structure of the object array: Ruddle & Lessels (2006) used a rectangular surrounding room and a rectangular grid-like structure of the pedestals with additional constraints (always one target and one decoy per group of four pedestals), whereas the current study did not contain any such regularities or other environmental geometry cues that participants could have used to remain oriented or re-orient. As the other procedural differences in the walking condition seem minimal, the large overall performance difference between our and Ruddle and Lessels's studies suggests that the rectangular structure of the room and object array layout was indeed an important factor for participants' ability to remain oriented in Ruddle & Lessels (2006), and could have served as a reference frame for remaining oriented in VR (McNamara, Sluzenski, & Rump, 2008). This hypothesis is in agreement with recent results by Kelly et al. (2008), who showed that the environmental geometry of the surrounding room in VR is an important factor for both spatial updating and reorientation. In particular, when the rectangular room was replaced by a cylindrical room devoid of orienting cues, participants got increasingly lost for increasing path lengths. Similarly, Riecke et al. (2005, 2007) showed that naturalistic environmental cues, but not optic flow alone, can be sufficient for spatial updating with performance approaching real-world performance, with or without concurrent physical motion cues.

Why Did Real Rotation Performance Approach Walking Performance in our Study, but not in Ruddle & Lessels (2006, 2009)? Ruddle & Lessels (2006) observed a clear performance benefit of walking over real rotation without physical translation, but the current study did not, despite using a similar navigational search task. Whereas the increase in task complexity due to the randomized target configuration and lack of environmental geometry in our study can explain the overall performance decrement, it seems unclear how task complexity could differentially affect performance in the walking versus real rotation condition. Hence, we propose that differences in the translational motion paradigm might be (at least in part) responsible for the observed differences: Ruddle & Lessels (2006) use a button-based translation control that allowed only forward motions and did not allow participants to continuously adjust their speed, whereas the current study used a joystick that allowed for continuous and intuitive control of translational velocities in the horizontal plane. Although further studies are needed to corroborate this conjecture, the current data highlights the importance of devising and carefully testing input-devices that allow for virtual locomotion with similar intuitive control, accuracy, and precision as actual walking while minimizing the cognitive load.

Why Did Real Rotation Performance Exceed Visual-Only Performance in our Study, but not in Ruddle & Lessels (2006, 2009)? Previous studies suggest that adding physical rotations cues can improve spatial orientation performance compared to visual-only simulations for various basic spatial tasks (Bakker, Werkhoven, & Passenier, 1999; Klatzky et al., 1998; Lathrop & Kaiser, 2002; Pausch et al., 1997).

However, for more complex spatial orientation and navigation tasks, there seems no clear evidence that physical rotations themselves improve performance, although providing full physical motions did prove to be beneficial. (Chance et al., 1998; Ruddle & Lessels, 2006, 2009). When asked to point to previously-encountered targets in a HMD-based maze tasks, participants pointed more accurately when walking as compared to pure joystick navigation (Chance et al., 1998). A real rotation condition where translations were joystick-controlled and rotations physically controlled yielded intermediate performance, with no significant differences relative to either walking or joystick condition. As discussed earlier, navigational search performance in (Ruddle & Lessels, 2006, 2009) showed no benefit of adding physical rotations over visual-only navigation. This is in contrast to the current study, which used the same navigational search task as (Ruddle & Lessels, 2006, 2009) but showed a clear benefit for added physical rotations. There are a number of factors that could have contributed to the observed differences:

First, Ruddle & Lessels (2006, 2009) used different displays (HMD vs. monitor) for the real rotation and visual-only rotation condition, whereas the current study used the same HMD for all conditions. Second, the navigational search task was likely more difficult in our study, as salient (re-)orienting cues such as the rectangular environment and the regular, rectangular object layout in (Ruddle & Lessels, 2006, 2009) were replaced by randomized object positions and orientations, thus largely avoiding salient orienting cues and intrinsic/extrinsic reference frames that participants could have used to remain oriented or re-orient during their simulated movements (Kelly et al., 2008; Riecke et al., 2005). Although further careful experimentation is needed, the comparison suggests that the availability of ample orienting cues in (Ruddle & Lessels, 2006, 2009) might have obscured potential effects of physical rotations, and that physical rotation cues might become more important under high cognitive load/task difficulty and limited availability of visual (re-)orienting cues.

Did Participants in the Joystick Condition Perform Poorly Because they Failed to Update their Heading? Previous studies investigating the updating of cognitive heading in VR showed individual differences in participants' strategies and the resulting systematic errors and underlying neural representation (Gramann, Muller, Eick, & Schonebeck, 2005; Iaria, Petrides, Dagher, Pike, & Bohbot, 2003). For example, using a point-to-origin paradigm after a visually simulated 2-segment excursion displayed on a desktop monitor, Gramann et al. (2005) reported that more than half of their participants responded as if they had not updated their heading and were still facing the original orientation. Gramann et al. interpreted these group of participants as “non-turners” who might have used an allocentric strategy that did not incorporate visually simulated heading changes. Klatzky et al. (1998) had reported similar failures to incorporate heading changes that were not physically performed but only visually displayed (in an HMD condition) or verbally instructed (in an imagine condition). Together, these studies suggests that participants in the current study might have shown comparable failures to update heading changes in the joystick condition where the visually simulated rotations were not physically performed, which might have contributed to the reduced task performance. The current experiment was, however, not designed to investigate this issue and does not allow for any specific conclusions, although informal observations suggest that the low overall performance in the joystick condition often coincided with being lost and disoriented. Additional reference frame conflicts between participants’ physical orientation in the lab and the simulated orientation in the joystick condition might have further contributed to the overall poor performance in the joystick condition (McNamara et al., 2008; Riecke, 2008).

Conclusions and Outlook Whereas previous studies showed a clear benefit of physical rotation cues only for simple spatial task (Bakker et al., 1999; Klatzky et al., 1998; Lathrop & Kaiser, 2002; Pausch et al., 1997), but not for more complex navigation tasks (Chance et al., 1998; Ruddle & Lessels, 2006, 2009), the current study provides first evidence that allowing VR users control simulated rotations with their own body can have significant benefits over mere joystick navigation. Moreover, navigation performance in this real-turn mode was statistically equivalent to performance for actual walking in six out of eight dependent variables, and the real-turn mode even reduced the amount of viewing direction changes significantly. These results suggest that, for many applications, allowing for full-body rotations without actual walking can provide considerable performance benefits, even for complex and cognitively demanding navigation tasks. These findings can help to reduce overall simulation effort and cost, as allowing users to walk through VR requires sufficiently large, position-tracked free-space walking areas and additional safety measures, whereas physical rotations can be implemented more easily and cost-effectively.

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