Are Left-Right Hemisphere Errors in Point-to-Origin Tasks in VR Caused by Failure to Incorporate Heading Changes?

Bernhard E. Riecke

Simon Fraser University, Surrey, BC, Canada
ber1@sfu.ca
http://iSpaceLab.com/Riecke

Abstract. Optic flow displays are frequently used both in spatial cognition/psychology research and VR simulations to avoid the influence of recognizable landmarks. However, optic flow displays not only lead to frequent misperceptions of simulated turns, but also to drastic qualitative errors: When asked to point back to the origin of locomotion after viewing simulated 2-segment excursions in VR, between 40% (Riecke 2008) and 100% (Klatzky et al., 1998) of participants responded as if they failed to update and incorporate the visually simulated turns into their responses. To further investigate such "NonTurner" behaviour, the current study used a wider range of path geometries that allow for clearer disambiguation of underlying strategies and mental processes. 55% of participants showed clear qualitative pointing errors (left-right hemisphere errors), thus confirming the reliability of the effect and the difficulties in properly using optic flow even in high-quality VR displays. Results suggest that these qualitative errors are not caused by left-right mirrored responses, but are indeed based on a failure to properly incorporate visually presented turns into point-to-origin responses. While the majority of these qualitative errors could be attributed to NonTurner behaviour as previously proposed, we identified a novel, modified NonTurner strategy that could reconcile prior findings. Finally, results suggest that Turners (which properly incorporate visually presented turns) might use online updating of the homing direction, whereas NonTurners resort to more effortful and cognitively demanding offline strategies. Better understanding these strategies and underlying processes and how they depend on stimulus and display parameters can help to inform the design of more effective VR simulations.

1 Introduction

How do we remain oriented while navigating through our environment? For both rotations and translations, the directions and distances between ourselves and surrounding objects of interest constantly changes when we move. Nevertheless, we often manage to remain oriented with seemingly little conscious effort, at least for shorter travels (May and Klatzky, 2000; Presson and Montello, 1994; Rieser, 1989). Whenever unique and recognizable features ("landmarks") are available, they provide a reliable means to remain oriented or recover orientation after disorientation. Hence, such **landmark-recognition based navigation** (or "**piloting**") is widely used whenever suitable landmarks are available (for extensive reviews, see Gallistel, 1990; Golledge, 1999; Loomis et al., 1999).

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Path integration is an alternative (and often complementary) approach for remaining oriented, and is based not on position-fixing, but on the continuous integration of velocity and acceleration information during travel (Loomis et al., 1999). Especially when landmarks are temporarily unavailable or unreliable (e.g., in fog or heavy snowfall, thick forest, or darkness), path integration plays a vital role and allows the navigator to remain oriented, at least for some time. For increasing time and distance of travel, however, path integration is prone to accumulating errors due to the integration process. Nevertheless, path integration can provide the basis for an automatic and robust continuous spatial updating mechanism that enables observers to remain oriented with little if any cognitive load or effort (Farrell and Robertson, 1998; Presson and Montello, 1994; Riecke, 2003; Rieser, 1989). It can thus serve as a reliable (as largely automated) backup mechanism should piloting ever fail. Moreover, path integration and spatial updating of our immediate environment can provide the scaffolding for learning landmarks and building up configural knowledge, even in animals as seemingly simple as desert ants (Müller and Wehner, 2010).

In order to disentangle the influences of piloting and path integration, the current study used an immersive, projection-based virtual reality setup. This enabled us to exclude all landmarks and focus solely on human visual path integration under full stimulus control and repeatability that is difficult to achieve in real-world settings. A typical and ecologically inspired experimental paradigm to study path integration in animals including humans is to require them to travel or point back to the origin of locomotion ("home") after an actual or simulated excursion (for reviews, see Etienne and Jeffery, 2004; Loomis et al., 1999; Maurer and Séguinot, 1995). One of the simplest yet nontrivial homing task is "triangle completion", where navigators are asked to return home after an excursion path consisting of a first straight segment s_1, a subsequent rotation by a given angle γ, and a final straight path segment s_2. Most animals including humans can perform such triangle completion fairly well as long as they are allowed to physically move, even in the absence of any landmark information (e.g., when blindfolded or when landmarks are removed). A similar experimental paradigm uses point-to-origin or turn-to-face-origin tasks at the end of the excursion instead of actual homing (Klatzky et al., 1998; Loomis et al., 1999). Although this does not allow for distance estimates, using pointing instead of locomotion to the origin allows for much shorter response times, as locomotion time is excluded as a potential confound. Experimentally, this enables us to more directly investigate different underlying mental processes and neural substrates, as the time for computing the homing response can be more tightly controlled, and participants do not have additional processing time during the return path (Gramann, 2012; Gramann et al., 2010; Riecke, 2008).

Path integration based on biomechanical and vestibular cues from blindfolded walking is generally believed to be sufficient for eliciting automatic spatial updating of self-to-surround relationships (Farrell and Robertson, 1998; Klatzky et al., 1998; Presson and Montello, 1994; Rieser, 1989). Can visual cues alone, in the absence of any supporting biomechanical or vestibular cues from physical motion, be sufficient to enable similar automatic spatial updating of our surrounding environment? Research suggests that providing a naturalistic, landmark-rich scene in immersive VR can indeed trigger spatial updating that is both **automatic** (in the sense that it occurs automatically and online during simulated self-motion and requires little conscious effort, attention, or deliberate intention) and **obligatory** (in the sense that it is difficult to intentionally suppress or ignore) (Riecke et al., 2007, 2005b). However, when landmarks were replaced by a simple optic flow stimulus, updating performance decreased and the stimulus could more easily be ignored (Riecke et al., 2007). Potentially related to this reduced availability of automatic spatial updating, participants in optic flow-based VR often seem to resort to offline strategies to solve the task at hand. For triangle completion or point-to-origin tasks, such offline strategies can include abstract geometric strategies, mental arithmetics, imagining top-down views or other configural strategies that rely on building up some kind of survey or configural representation of the travelled path and pointing targets (Riecke, 2008; Riecke et al., 2002). Usage of such offline strategies might contribute to the finding that homing or point-to-origin performance often correlates with general mental spatial abilities.

A particularly striking example of strategy switch and resulting qualitative errors has been reported in a seminal paper by Klatzky et al. (1998), when they compared a variety of different locomotion conditions. Using a modified point-to-origin paradigm, participants were asked to physically turn to face the origin as if they had actually walked the 2-segment trajectory and were now at the end of it. While participants performed relatively accurately in a blind walking condition, they showed qualitatively different response patterns when they did not physically move but instead only watched someone else walk the 2-segment path, listened to a verbal description of the trajectory, or watched optic flow fields of the excursion path on a head-mounted display (HMD). That is, whenever participants did not move, they responded as if they did not update their cognitive heading during the turn, but instead responded as if they were at the end of the excursion pathway, but still facing their original orientation, as illustrated in Figure 1. In their study, optic flow presented on a HMD with a field of view (FOV) of $44° \times 33°$ was in general insufficient to elicit spatial updating that enables correct updating of simulated heading changes. Only when the visually simulated rotations were accompanied by matching physical rotations did participants properly incorporate the rotations into their point-to-origin response.

Later studies reported similar failures to properly update rotations that are only visually simulated via optic flow, although the percentage of such "NonTurners" never reached 100% but typically averaged around 50% (Gramann et al., 2005, 2011; Riecke, 2008). To avoid such failures to update visually presented rotation in VR, several researchers have resorted to providing advance feedback training that allowed participants to correct their initial errors (Gramann et al., 2005; Lawton and Morrin, 1999; Mahmood et al., 2009; Riecke et al., 2002; Wiener and Mallot, 2006). But even with advance feedback training, optic flow-based point-to-origin tasks never seem to reach the ease, intuitiveness, and low cognitive load of blindfolded walking tasks, where failures to update rotations are virtually unknown (Easton and Sholl, 1995; Farrell and Robertson, 1998; Klatzky et al., 1998; Loomis et al., 1999). This might, at least in part, be related to to the finding that biomechanical and vestibular cues from blind walking are sufficient to induce automatic and obligatory spatial updating of our immediate surroundings (Farrell and Robertson, 1998; Klatzky et al., 1998), whereas optic flow-based visual cues (i.e., without landmarks) are typically not, often resulting in increased response times and errors (Chance et al., 1998; Klatzky et al., 1998; Lawton and Morrin, 1999; Riecke, 2008; Riecke et al., 2007; Wiener and Mallot, 2006). In a way, this bears similarity to the well-documented difficulty in imagining perspective switches, where response times are fairly long and errors increase the more the to-be-imagined orientation differs from one's physical orientation (Easton and Sholl, 1995; Farrell and Robertson, 1998; May, 1996; Presson and Montello, 1994; Rieser, 1989).

In summary, whenever online automatic spatial updating is induced by the available sensorimotor cues (e.g., from blind walking), participants can and typically do rely on this updating process to maintain orientation and a sense of the homing direction during the excursion path. In situations where the available stimuli are insufficient to elicit online automatic spatial updating (e.g., for verbal descriptions and most optic flow-based displays), however, participants often seem to resort to offline and/or cognitively more demanding strategies such as configural updating or mental arithmetic. One the one hand, this can lead to increased response times and perceived task difficulty. On the other hand, it can lead to qualitative errors such as the failures to properly incorporate self-rotations as discussed above (Gramann et al., 2005; Klatzky et al., 1998; Riecke, 2008).

The current study was designed to further investigate the phenomenon of left-right hemisphere errors such as the failure to incorporate heading changes as proposed by Klatzky et al. (1998). In particular, we used a much wider range of excursion path geometries than prior studies (Avraamides et al., 2004; Gramann et al., 2005, 2010; Klatzky et al., 1998; Riecke, 2008) to be able to disambiguate between different potential underlying strategies and processes. These potential underlying strategies are discussed below and illustrated in Figure 1 for one specific path geometry.

Turner. Among the four strategies discussed here, the Turner strategy is the only one that does not lead to systematic left-right hemisphere errors. Turner behavior is the default expected behavior if participants properly update the (real, simulated, or verbally instructed) orientation changes during the outbound path (see Figure 1, left). Note that systematic and random errors can, of course, still originate from misperceptions of the path geometry and in particular the turning angle, or other systematic or random sources of errors, e.g., during encoding, mental computation or updating of the homing direction, or execution of the pointing response (Fujita et al., 1990; Riecke et al., 2002).

NonTurner. Klatzky et al. (1998) were the first to describe the apparent failure of participants to update heading changes in situations where the rotations were not physically performed. That is, participants responded as if they were still facing their original orientation, as illustrated in Figure 1, right. Klatzky et al. (1998) were, however, careful in stating that "It is possible that subjects also have an imagined heading that is updated but does not govern their response" (p. 297). Indeed, a follow-up study by Avraamides et al. (2004) showed that participants responded correctly if a verbal response (e.g., "left, 120 degrees") was used instead of the body-referenced response of physically turning to face the origin. The authors proposed that participants indeed successfully updated an imagined (or "cognitive") heading in all conditions, but somehow did not use this imagined heading for the bodily pointing response. This might be caused by a reference frame conflict between the updated imagined (or cognitive) heading and their physical (or "perceptual") heading, as discussed in more detail in (Avraamides and Kelly, 2008; Avraamides et al., 2004; Gramann, 2012).

Left-right inversion. Although most of the prior data on left-right hemisphere errors could be explained by such failure to properly incorporate heading changes into point-to-origin responses, Riecke (2008) observed several cases of left-right hemisphere errors which could not be explained by simple failures to properly update and incorporate heading changes into the pointing responses. In their study, the second path segment s_2 was either of the same length or shorter than the first segment s_1, a fact that participants were aware of. These path layouts predict that NonTurners should always point into the rear (posterior) hemisphere, but never into the frontal (anterior) hemisphere. Five of the 17 participants showing consistent left-right hemisphere errors, however, did consistently point into the frontal (anterior) hemisphere for larger turning angles. This led Riecke (2008) to propose that these participants might not have failed to update their heading properly, but instead produced left-right mirrored responses (cf. Figure 1), potentially because they were "initially uncertain about the correct response, or somehow puzzled or distracted by the visual simulation, and initially picked the left-right mirrored response and then continued to do this, resulting in consistent left-right swap errors" (p. 169). In fact, for 2-segment paths where $s_1 = s_2$ (which is most commonly used in the literature), NonTurner and left-right inversion strategies produce identical predictions. Only for unequal segment length do the predictions differ, as illustrated in Figure 1 and 3. This motivated us to include conditions where s_1 and s_2 are vastly different to allow for clearer disambiguation between potential strategies underlying left-right hemisphere errors.

NonTurner pointing to turning position x_1. Finally, careful re-analysis of the five proposed left-right inverter cases in Riecke (2008) suggests an alternative possible strategy that could equally explain those data, but has not been previously described or discussed to the best of our knowledge. That is, we propose here that those participants might also be NonTurners, but instead of pointing to the origin of locomotion as instructed, they consistently pointed to the turning position x_1, as indicated in Figure 1 and 3. Although it is yet unclear why participants might use such a simplified NonTurner strategy, it can easily explain why the five proposed left-right inverter participants in Riecke (2008) pointed in the frontal (anterior) hemisphere for larger turning angles (see Figure 3, middle and bottom plots).

1.1 Goals, Research Questions, and Hypotheses

The current study extends our earlier work (Riecke, 2008) and was designed to investigate a series of research questions and hypotheses as described below. In particular, the study was designed to further our understanding of potential underlying factors and mechanisms leading to systematic left-right hemisphere errors in point-to-origin tasks that do not allow for physical turning.

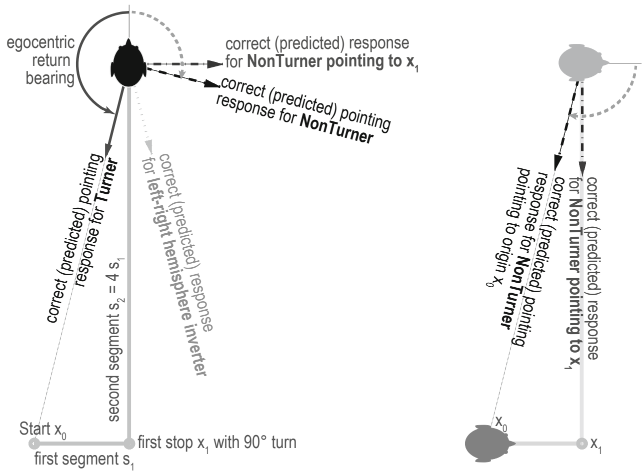

Fig. 1. Left: Top-down schematic illustration of predicted pointing responses for the different potential underlying strategies. **Right:** Illustration of NonTurner pointing strategy that does not incorporate the heading change into their pointing response, such that they act as if still facing the original orientation they had at the start position x_0.

Occurrence of left-right hemisphere errors. Similar to earlier studies using optic-flow-based point-to-origin tasks (Gramann et al., 2005, 2010, 2011; Riecke, 2008), we expect around 50% of participants to systematically show qualitative pointing errors, in that they systematically point into the left-right inverted hemisphere (e.g., for left turns they point into the right instead of the left hemisphere).

What processes underly left-right hemisphere errors? As detailed above, a central goal of this study was to disambiguate between the three proposed strategies that might underly left-right hemisphere errors: Left-right inversion, failure to update heading changes (NonTurner), or failure to update heading changes combined with pointing to the turning position x_1 instead of the origin (NonTurner pointing to x_1).

Are left-right hemisphere errors related to problems understanding task instructions and demands? Although previous research consistently showed the existence of left-right hemisphere errors in optic-flow-based point-to-origin tasks unless participants received explicit feedback training, it is conceivable that participants might have somehow misunderstood or misinterpreted the experimental task and procedure. If this were the case, than the occurrence and number of left-right hemisphere errors should decline if participants are provided with advance easy-to-understand task instructions. To this end, participants in the current study completed prior to the VR tests a real-world practice phase, in which they were blindfolded and led to walk along several 2-segment paths at the end of which they pointed back to the origin of locomotion using the identical pointing device as in the later VR experiment. We hypothesized that this task should be easy and lead to almost error-free pointings, and thus exclude all potential misunderstandings of experimental demands in the subsequent VR experiment.

Is the occurrence of left-right hemisphere errors related to general spatial abilities? If so, this would predict that NonTurners would on average show lower spatial abilities (tested here using a standard spatial abilities test as well as self-reported general spatial abilities) as compared to Turners that do not show such left-right hemisphere errors. In addition, we hypothesized that NonTurners might perceive the task as more difficult (which we assessed using post-experimental task difficulty ratings). While Riecke (2008) showed significantly lower spatial abilities test scores for participants showing left-right hemisphere errors, they found surprisingly no signifiant difference in terms of task difficulty ratings. The current study aims to test if these trends can be corroborated.

How do previous point-to-origin results extend to more extreme path geometries? In previous studies, the length of the first and second segment was typically either identical (as in (Gramann et al., 2005) or half of the trials in (Riecke, 2008)), or they were fairly similar in length such that participants might not have realized this or incorporated into their responses. In fact, our previous study (Riecke, 2008) revealed that participants could not reliably assess if the path length of the first and second segment were the same or differed by 50%. When asked to judge the relative length of s_1 versus s_2 in two post-experimental trials, 62.5% responded erroneously for an isosceles excursion path (where $s_1 = s_2$), and 16.7% mistook a path were the first segment was 50% longer than the second segment ($s_1 = 1.5 \times s_2$) as an isosceles path. The current experiment was designed to investigate if and how prior findings might extend to more uncommon path geometries where the first and second path segment have significantly different lengths. To this end, we compared the previously-used isosceles ratio of $s_1/s_2 = 1$ with two more extreme ratios of $s_1/s_2 = 1/4$ and $s_1/s_2 = 4$. Using these path geometries also allowed us to almost double the range of correct egocentric homing directions: Whereas isosceles paths with $s_1 = s_2$ yield correct egocentric pointing directions between 90°-180° (i.e., for left turns the origin will always be somewhere left and behind of the observer), using first segments that are considerably longer than the second segment (here: $s_1/s_2 = 4$) extends this range of correct egocentric pointing directions to almost 0°-180° (i.e., for left turns the origin will always be somewhere to the left, but could now also be in the frontal hemisphere).

2 Methods

Twenty participants (7 female) aged 20-32 years (mean: 24.3) completed the experiment for standard payment. All participants had normal or corrected-to-normal vision. Note that methods of the current experiment were held similar to our earlier study (Riecke, 2008) to allow for direct comparison.

2.1 Stimuli and Apparatus

Throughout the experiment, participants were seated 89cm from a flat projections screen (1.68m × 1.26m, corresponding to a field of view of about 84° × 63°), as illustrated in Figure 2. Visual stimuli were projected non-stereoscopically using a JVC D-ILA DLA-SX21S video projector with a resolution of 1400 × 1050 pixels. The virtual scene was designed to resemble a flat grass plane and provided ample optic flow and high contrast, but no landmarks. To exclude ambient sound that could have interfered with the task, participants wore active noise cancellation headphones (Sennheiser HMEC 300) displaying broad-band masking noise (an unobtrusive mix of river sounds). In addition, black curtains surround the whole setup to ensure that participants could neither see nor hear the actual surrounding lab. Pointing was performed using a modified gamepad, where the central knob was replaced by a 18cm long thin plastic rod to allow for more accurate responses (Riecke, 2008). The pointer was mounted above participants' lap to ensure correct alignment and ease-of-use.

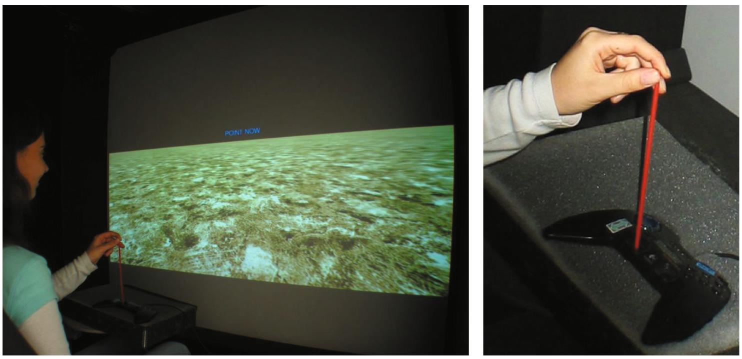

Fig. 2. Experimental setup: Participants with pointing device (modified gamepad) seated behind projection screen showing grass-like ground plane environment devoid of landmarks.

2.2 Procedure and Experimental Design

Participants' task was to point back to the origin of locomotion after visually displayed 2-segment trajectories. Trajectories consisted of a first segment s_1 (8m/s maximum velocity, with brief initial acceleration and final deceleration phase to avoid motion sickness), followed by a turn on the spot (30°/s rotational velocity), and a subsequent second segment s_2 (same velocity profile as s_1). The turning direction was alternated between trials to reduce the occurrence of potential motion aftereffects and motion sickness, but was not analyzed separately as it was not the focus of this study. Hence, the data were pooled over the turning direction for all analyses. Previous research had shown that participants in lab situations tend to resort to computationally expensive cognitive strategies (like mental trigonometry or algebra) to come up with the desired response, especially if response times are unlimited and performance feedback is provided (Gramann et al., 2005; Lawton and Morrin, 1999; Riecke et al., 2002; Wiener and Mallot, 2006). As we were interested in investigating participants' natural and intuitive spatial orientation/spatial updating in VR and reducing the influence of higher cognitive strategies, we instructed participants to point "as accurately and quickly as possible" and to point as if they had physically moved. Participants were never provided with any performance feedback to reduce potential effects of re-calibration and higher cognitive strategies. Using a within-participant design, each participant completed the following phases:

Demonstration Phase. Before starting the experiment, participants gave informed consent and received written and aural instructions. Participants then watched the experimenter perform three randomly selected trials while explaining the experimental procedure and pointing device. Care was taken that the pointing response of the experimenter was random such that participants did not model their responses.

Real-World Practice Phase. A real-world blind-walking point-to-origin pre-test was performed to serve as a baseline for the subsequent VR experiments. To this end, participants were blindfolded and donned the unplugged pointing device. They were led along nine different 2-segment paths, and at the end of each path asked to point back to the origin of locomotion using the pointing device. The experimenter visually judged the accuracy of the pointings. Unknown to the participants, path geometries were a subset of the geometries used in the subsequent VR experiment, in randomized order per participant (length of first segment s_1={1m, 2m, 3m) × turning angle γ={30°, 90°, 150°}; s_2 was adjusted such that the total path length was about 4m). Before the next trial they were led on a circuitous path to a new, randomly selected starting location. Participants responses were virtually error-free, and participants reported that the real-world pointing task was easy and intuitive to perform. Note that none of the participants showed any failures to properly update the rotations, confirming results by Klatzky et al. (1998). For the subsequent VR conditions, participants were instructed to treat the displayed visuals as if they originated from actual self-motion, and to respond as if they had actually moved, just like in this real-world practice phase. These instructions were chosen to ensure that all participants fully understood the experimental demands and in particular the pointing instructions.

2-Segment VR Practice Experiment. In order to reduce the impact of potential learning effects on the main experiment, all participants first performed a VR practice experiment, which used different turning angles than the subsequent main experiments to avoid direct transfer or memorization of turning angles. Each participant completed 14 trials, composed of a factorial combination of 3 lengths of the first straight segment s_1={6m, 15m, 24m) × 2 turning angles γ={60°, 120°} × 2 turning directions (left, right; alternating), plus 2 additional baseline trials without any rotation (γ=0°). s_2 was adjusted such that the total path length was always 30m.

2-Segment VR Main Experiment. Subsequently, participants performed 40 trials in the main 2-segment VR experiment, consisting of a factorial combination of 3 lengths of the first straight segment s_1={6m, 15m, 24m} × 3 turning angles γ={30°, 90°, 150°} × 2 turning directions (left, right; alternating) × 2 repetitions per condition (blocked), plus 4 randomly interspersed baseline trials without any rotation (γ=0°). As before, s_2 was adjusted such that the total path length was always 30m.

Mental Spatial Abilities Test and Debriefing. A standard paper-and-pencil mental spatial abilities test was used to investigate possible correlations between general mental spatial abilities and pointing performance as well as strategy choice (turner vs. Non-Turner) (Stumpf and Fay, 1983). A previous VR study (Riecke et al., 2002) demonstrated significant correlations between triangle completion performance and mental spatial abilities using the same test, such that we expected sufficient sensitivity for the current study. Subsequently, participants were debriefed, paid, and thanked for their participation.

3 Results and Discussion

Pointing data are summarized in Figure 3 and 4. In the real-world practice phase, all participants were able to point back to the origin of locomotion with negligible errors after being blindfolded and led along 2-segment excursion. In the virtual reality conditions, most participants still pointed fairly consistently, as indicated by the circular mean pointing vectors almost touching the unity circle in Figure 3 (Batschelet, 1981). Pointing directions showed, however, considerable between-participants variability as well as systematic pointing errors, especially for larger turning angles, potentially due to a misestimation of the visually presented turning angle.

3.1 Occurrence of Left-Right Hemisphere Errors

In addition to the errors described above, eleven of the 20 participants consistently showed qualitative (and not just quantitative) pointing errors in that they consistently pointed into the wrong (left-right inverted) hemisphere (see Figure 3). That is, for a 2-segment path including a left turn, they pointed to the right hemisphere instead of the left hemisphere and vice versa. Participants consistently showing such left-right hemisphere errors will be termed “NonTurners” in the following, as their behavior might be explained by a failure to properly integrate the visually presented turns into their egocentric pointing response (Avraamides et al., 2004; Gramann et al., 2005; Klatzky et al., 1998; Riecke, 2008). Conversely, participants generally pointing into the correct (instead of left-right inverted) hemisphere will be termed “Turners” here, as they respond as if they update and incorporate the visually presented turns at least qualitatively correct, even though they might misestimate the turning angle.

As pointing data is inherently noisy, we computed the ratio of trials with left-right hemisphere errors per participants to reliably and automatically categorize participants. Nine participants (with IDs 2, 4, 5, 7, 8, 10, 17, 18, and 19) were thus categorized as Turners, with a mean ratio of left-right hemisphere error trials of 7.8%. The remaining eleven participants were categorized as NonTurners, with a mean ratio of hemisphere error trials of 87.4%. Note that none of the Turners or NonTurners showed any left-right hemisphere errors in the prior real-world practice phase. This suggests that the NonTurners’ qualitative pointing errors in VR are neither based on a failure to understand the instructions nor a failure to use the pointing device properly, as the same instructions and pointing device were used in the real-world practice phase.

3.2 Statistical Analysis

Data were analyzed using separate repeated measures ANOVAs for the dependent measures response time and signed pointing error. Independent variables for in the ANOVAs included the within-participant factors turning angle γ and length of the first segment s_1,

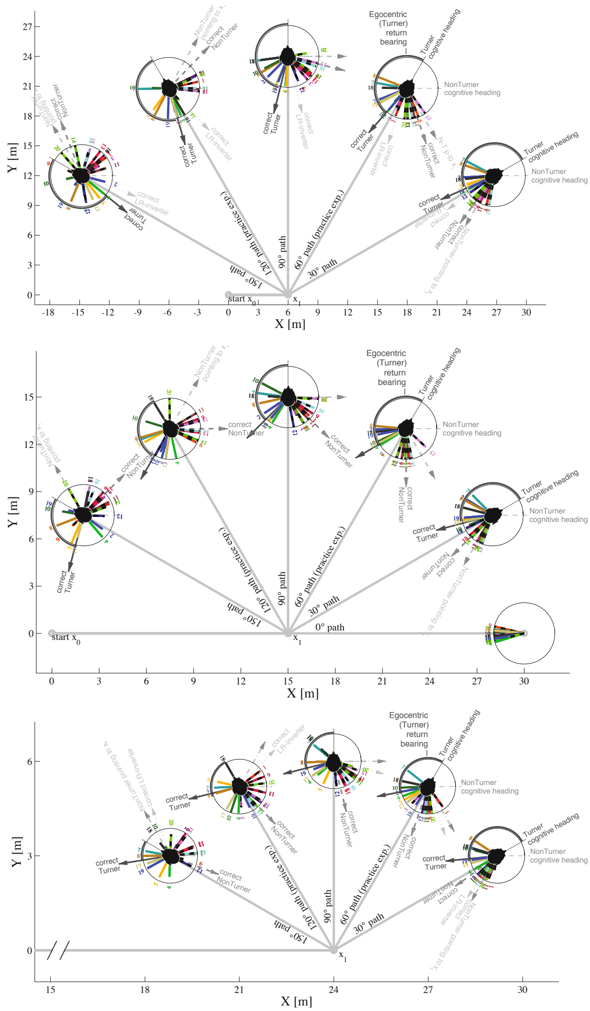

Fig. 3. Top-down schematic view of the outbound 2-segment paths (solid gray lines) for the three different values of s_1. Data from the practice experiment (60° and 120° turns) and the main experiment (30°, 90°, and 150° turns) are combined here for comparability. Circular mean pointing directions for each participant are indicated by solid bars for Turners and dashed bars for Non-Turners. Numbers indicate participants numbers. The length of the circular mean pointing vector indicates the consistency of the individual pointing directions: Shorter mean pointing vectors indicate higher circular standard deviations of the individual pointing (e.g., participant 10), whereas mean pointing vectors close to the surrounding black unity circle indicate high consistency and thus low circular standard deviations of the individual pointings (e.g., participant 20; Batschelet, 1981). Correct homing vectors are plotted as a solid black arrow labeled “correct Turner”. Predicted pointing vectors for participants that simply show left-right mirrored responses are labeled “correct LR-inverter”, whereas predicted pointing vectors for “NonTurner” participants that act as if they did not update their cognitive heading such that they still face the original orientation (0°) are labeled “correct NonTurner”.

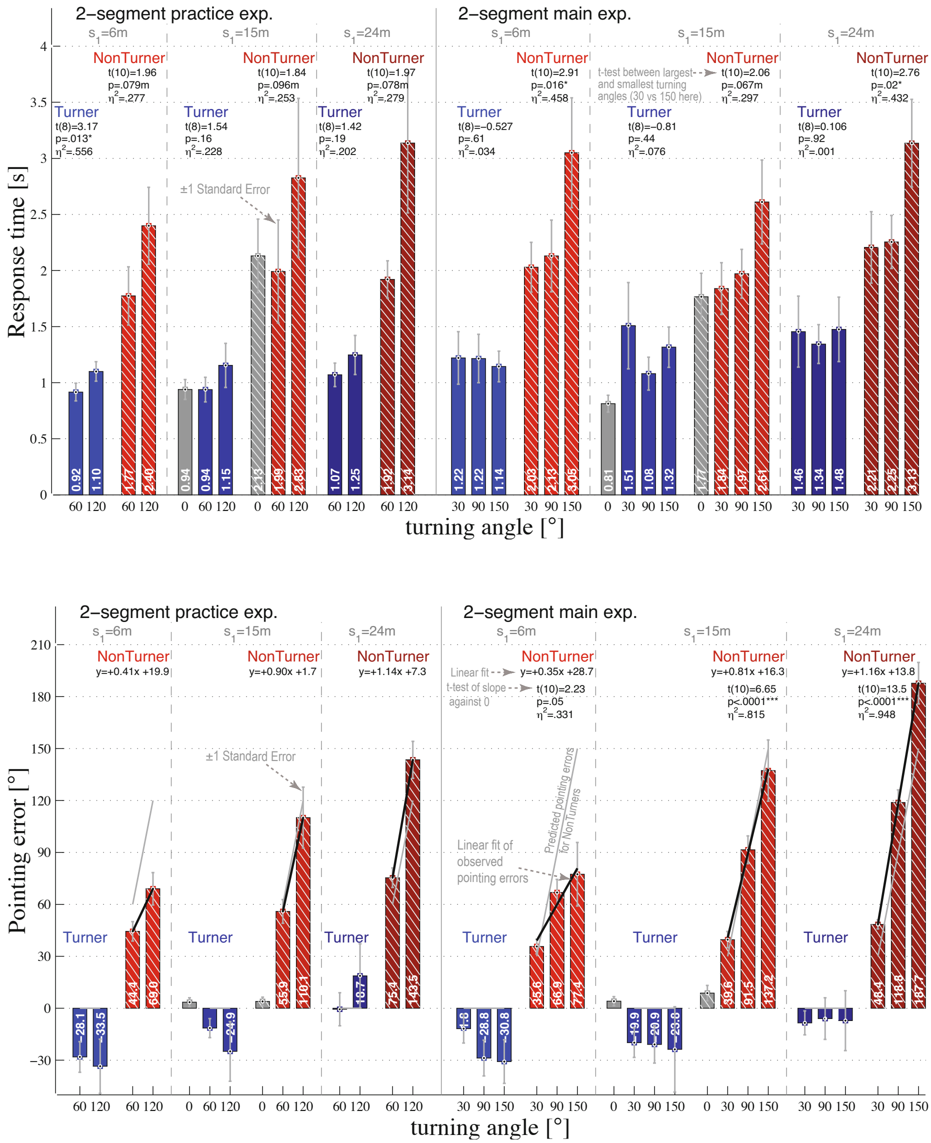

Fig. 4. Arithmetic means ± 1SEM of response time (top) and the signed pointing error (bottom) for the different experiments and path geometries. Turner (solid bars) and NonTurner (hatched bars) are plotted separately to show differences in response patterns.

Table 1. ANOVA results for practice experiment (top) and main experiment (bottom). Significant effects are typeset in bold, marginally significant effect in italics; * p<.05, ** p<.01, *** p<.001.

Practice experiment	Pointing error			Response time		
	F	p	η_p^2	F	p	η_p^2
LR-hemisphere errors	**F(1,18) = 77.9**	**p <.001*****	**.812**	**F(1,18) = 84.0**	**p <.001*****	**.824**
Length of first segment s_1	**F(2,36) = 24.7**	**p <.001*****	**.578**	F(21.3,1.18) = .821	p = .394	.004
s_1 × LR-hemisphere errors	F(2,36) = .670	p =.518	.036	F(21.3,1.18) = .255	p = .658	.014
Turning angle γ	**F(1,18) = 13.7**	**p =.002****	**.433**	**F(1,18) = 8.75**	**p = .008****	**.327**
γ × LR-hemisphere errors	**F(1,18) = 13.6**	**p =.002****	**.430**	*F(1,18) = 3.65*	*p = .072m*	*.168*
s_1 × γ	**F(2,26) = 3.85**	**p =.030***	**.176**	F(1.38,24.9) = .357	p = .625	.019
s_1 × γ × LR-hemisphere err.	F(2,36) = 1.13	p =.335	.059	F(1.38,24.9) = .392	p = .604	.021

Main experiment	Pointing error			Response time		
	F	p	η_p^2	F	p	η_p^2
LR-hemisphere errors	**F(1,18) = 35.7**	**p <.001*****	**.665**	**F(1,18) = 109.9**	**p <.001*****	**.859**
Length of first segment s_1	**F(2,36) = 38.5**	**p <.001*****	**.681**	**F(2,36) = 5.04**	**p = .012***	**.219**
s_1 × LR-hemisphere errors	**F(2,36) = 12.2**	**p <.001*****	**.404**	*F(2,36) = 2.65*	*p = .084m*	*.128*
Turning angle γ	**F(1.18,21.3) = 17.2**	**p <.001*****	**.488**	**F(1.52,27.3) = 6.19**	**p = .010****	**.256**
γ × LR-hemisphere errors	**F(1.18,21.3) = 23.5**	**p <.001*****	**.567**	**F(1.52,27.3) = 6.38**	**p = .009****	**.262**
s_1 × γ	**F(2.49,44.8) = 8.79**	**p <.001*****	**.329**	F(4,72) = .366	p = .832	.020
s_1 × γ × LR-hemisphere err.	**F(2.49,44.8) = 4.07**	**p = .017***	**.184**	F(4,72) = .637	p = .638	.034

and the between-participant factor left-right hemisphere errors (Turner vs. NonTurner, as analyzed above). The baseline condition of γ=0° was excluded from the ANOVAs and data were pooled over the turning direction (left/right) as this was not a focus of the current study. Greenhouse-Geisser correction was applied where needed. ANOVA results are summarized in Table 1.

3.3 Pointing Errors

As expected, overall pointing errors were significantly larger for NonTurners as compared to Turners (cf. Figure 4 and Table 1). Mean pointing errors for NonTurners were 83.1° (standard error: 7.3°) in the practice experiment and 89.2° (SE: 8.1°) in the main experiment, as compared to Turner pointing errors of -13.3° (SE: 8.1°) for the practice experiment and -17.5° (SE 8.9°) for the main experiment. That is, while NonTurners showed a considerable general underestimation of turning angles (as would be predicted if they indeed failed to update the turns), Turners showed a slight overall overestimation of visually presented turns. As indicated in Figure 4, NonTurners showed larger pointing errors for increasing turning angles (as predicted by failure to update rotations). This is corroborated by the linear fit slopes being significantly above zero for all lengths of s_1 (see t-test insets in Figure 4). Especially for s_1 = 15m and s_1 = 24m, NonTurners' overall pointing errors were remarkably close to the values predicted by a failure to update the rotation and pointing as if still being in the original (0°) orientation, depicted as solid gray lines in Figure 4. Pointing errors for Turners, however, showed no overall dependence on turning angles. Although there was large between-participant variability in pointing errors (cf. Figure 3), average pointing errors for Turners as well as NonTurners were fairly close to the predicted values.

3.4 Response Times

Mean response times were relatively low, both in the practice experiment (1.71s, SE: .28) and the main experiment (1.83s, SE: .18s). Turners showed significantly lower response times than NonTurners, both for the practice experiment (1.07s vs. 2.34s, respectively, F(1,18 = 11.6, p=.003**, η_p^2 = .393) and the main experiment (1.31s vs. 2.36s, F(1,18 = 9.04, p=.008**, η_p^2 = .334). For the practice experiment, both Turners and NonTurners showed a tendency towards increased response times for larger turning angles, as indicated by the significant main effect of turning angle γ on response time (see ANOVA results in Table 1), the lack of significant interaction between turning angle and LR-hemisphere errors, and the pair-wise t-tests between smallest and largest turning angles in Figure 4. For the main experiment, however, Turners showed no longer any tendency towards increased response times for larger turns, whereas NonTurners still showed longer response times for larger turns. This is supported by the significant interaction between turning angle γ and left-right hemisphere errors (see Table 1) and t-tests in Figure 4. This dichotomy corroborates the hypothesis that Turners and NonTurners use different underlying strategies to solve the pointing task.

3.5 Correlation between Behavioral and Post-experimental Data

Data from the post-experimental questionnaire and mental spatial abilities test are summarized in Figure 5. Although Figure 5 (a) suggests a tendency for NonTurners to score lower on the mental spatial abilities test (Stumpf and Fay, 1983) than Turners, this tendency did not reach significance. Note that this differs from previous findings by Riecke (2008), who observed significantly lower mental spatial abilities measures for NonTurners. This might be related to a different participant group used and/or insufficient statistical power due to only testing 20 participants in the current study. When asked to rate their everyday spatial orientation ability on a scale from 0-10, NonTurners scored somewhat lower than Turners (6.59 vs. 7.94). This trend did not reach significance, though, corroborating similar findings by Riecke (2008, Experimental series 2).

Similar to findings by Riecke (2008), there was a slight but non-significant tendency for males to perform higher on the mental spatial abilities test and the self-reported spatial orientation ability in the current study (cf. Figure 5 (a) & (b)). Note that we did not find the clear gender effects that are often reported for various spatial abilities (see reviews by Coluccia and Louse, 2004; Lawton and Morrin, 1999). Again, insufficient power and differences in participant population might both have contributed to the lack of gender effects in the current study. Turner and NonTurner did not differ significantly in terms of their age (t(18)=-1.54, p=.14, η^2=.116), amount of daily computer usage (t(18)=-.0218, p=.98, η^2=.10), or rated task difficulty (t(18)=-592, p=.56, η^2=.019). This corroborates our earlier findings (Riecke, 2008). Similarly, there was no significant influence of gender on any of these measures (all p>.17).

4 General Discussion and Conclusions

The current study was designed to investigate the phenomenon of left-right hemisphere errors that occur in point-to-origin tasks where participants do not physically execute the turn between the first and second segment (Avraamides et al., 2004; Gramann et al., 2005, 2010, 2011; Klatzky et al., 1998; Riecke, 2008).

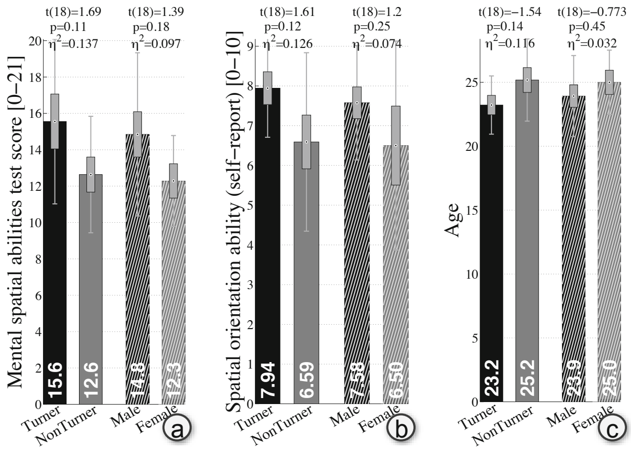

Fig. 5. Data from the post-experimental questionnaire. Boxes and whiskers denote ± 1SEM and ±1SD, respectively. Top insets show results from unpaired t-tests for Turner vs. NonTurner (left solid bars) and gender (right hatched bars).

4.1 Occurrence of Left-Right Hemisphere Errors

The general phenomenon of left-right hemisphere errors was confirmed in the current study, with 55% of the current participants showing such qualitative errors in their pointing responses. As detailed in Table 2, this percentage of left-right hemisphere errors was slightly larger than in (Riecke, 2008), and roughly comparable to Gramann et al. (2005, 2010, 2011). A recent study by Sigurdarson et al. (2012) showed that left-right hemisphere errors can occur even when visually simulated rotations are accompanied by matching physical rotations. This challenges the notion that physical rotations necessarily induce automatic and obligatory spatial updating (Klatzky et al., 1998; May and Klatzky, 2000; Presson and Montello, 1994; Rieser, 1989).

Table 2. Relative distribution of NonTurners amongst male and female participants

Study	Total # participants	% NonTurner	% NonTurner for males	% NonTurner for females
Current	20 (13 male)	55% (11/20)	31% (4/13 males)	100% (7/7 females)
Riecke (2008), Exp. 1	16 (half male)	38% (6/16)	13% (1/8 males)	63% (5/8 females)
Riecke (2008), Exp. 2	24 (half male)	46% (11/24)	33% (4/12 males)	58% (7/12 females)
Current + Riecke (2008)	60	47% (28/60)	27% (9/33 males)	70% (19/27 females)

4.2 What Processes Underly Left-Right Hemisphere Errors?

Using an unusually wide range of triangle geometries in the current study allowed us to use the behavioral (pointing) data to disambiguate between the potential strategies underlying left-right hemisphere errors. First of all, we found no direct support of left-right inversion strategies: As indicated in Figure 3 (top), left-right inversion would have predicted that participants in the $s_2 = 4 \times s_1$ conditions should always point into the far rear (posterior) hemisphere, with little dependence on the turning angle γ. This was not observed. Instead, participants showing left-right hemisphere errors pointed into the far posterior direction for small turning angles and increasingly towards more frontal (anterior) directions for increasing turning angles. While not compatible with left-right inversion, this behavior is compatible with both NonTurner strategies (cf. Figure 3 (top)). Note that participants might have misestimated turning angles (Riecke et al., 2005a), such that we refrain from a more quantitative analysis of the exact pointing angles when trying to disambiguate between potential underlying strategies.

Previous studies showed that participants in general use a chosen strategy quite consistently (Avraamides et al., 2004; Gramann, 2012; Gramann et al., 2005, 2010, 2011; Klatzky et al., 1998; Riecke, 2008). Hence, we assume here that participants did not switch strategy for the different path geometries. This is essential, as left-right inverter and NonTurner (pointing to the origin, not x_1) strategies yield identical predictions for the isosceles path geometries where $s_2 = s_1$. As indicated in Figure 3 (middle), analyzing the pointing data from the isosceles path geometries where $s_2 = s_1$ thus allows us to disambiguate between the NonTurner strategies where participants point to the turning position x_1 and the default NonTurner strategy where they point (as instructed) towards the origin of locomotion x_0. Whereas the latter (default NonTurner) strategy predicts that participants should never point into the frontal (anterior) hemisphere as long as $s_2 \leq s_1$, NonTurners pointing to x_1 would be expected to point into the frontal hemisphere for the largest turning angles (γ=120° and γ=150°). This was indeed observed for one participant (#20, depicted as green dashed line in Figure 3), who pointed into the frontal hemisphere for γ=120° and γ=150°. The remaining ten participant showed pointing behavior roughly consistent with predictions from the default NonTurner strategy, in that they did not point into the frontal hemisphere as long as $s_2 \leq s_1$.

A similar response pattern was observed for the trials where the second segment was much shorter than the first one ($s_2 = 1/4 \times s_1$), as indicated in Figure 3 (bottom): Whereas participant #20 pointed again into the frontal hemisphere for the largest turning angle, the remaining 10 participants always pointed into the rear (posterior) hemisphere, which is consistent with the default NonTurner behavior for $s_2 \leq s_1$.

To complement this visual inspection of the data with an algorithmic and thus less subjective and more easily reproducible approach, we mathematically compared participants' pointing directions with predictions from each of the four proposed strategies: Turner, NonTurner, NonTurner pointing to x_1, and left-right inverter, as illustrated in Figure 3. To this end, we defined an error measure as the absolute difference between observed and predicted pointing directions for each condition and strategy, and used that to algorithmically categorize each participant: e.g., if this error measure was lowest for Turner predictions for a given participant, (s)he was categorized as a Turner. Incidentally, this algorithmic categorization led to identical categorization as this visual inspection described above, thus corroborating the earlier analysis: Participants 2, 4, 5, 7, 8, 10, 17, 18, and 19 were categorized as Turner (as in subsection 3.1 above), participant 20 as NonTurner pointing to x_1, and the remaining participants were categorized as regular NonTurner, with no participant being categorized as left-right inverter.

In summary, the current data suggest that the vast majority of participants showing consistent left-right hemisphere errors indeed simply failed to properly update the visually simulated heading change and respond accordingly, as proposed previously (Avraamides et al., 2004; Gramann, 2012; Gramann et al., 2005, 2010, 2011; Klatzky et al., 1998; Riecke, 2008). While we did not find support for a left-right inversion strategy, one participant consistently seemed to use a different strategy that is inconsistent with the default NonTurner strategy. We hypothesize that this participants did not incorporate heading changes (just as NonTurners), but in addition pointed not to the origin of locomotion as instructed, but instead to the position x_1 where the turn took place. Careful reanalysis of the (Riecke, 2008) data suggests that this strategy (NonTurner pointing to x_1) can indeed explain the data from those 5 participants that pointed into the frontal hemisphere and thus could not simply be explained by a normal NonTurner strategy. Further, carefully designed experiments are needed, though, to corroborate these hypotheses.

Are left-right hemisphere errors related to problems understanding task instructions and demands? In the current study, all participants performed a real-world practice phase, where they were blindfolded and led along several 2-segment excursion paths before being asked to point to the origin of travel using the same pointing device that was used in the subsequent VR experiment. As expected, participants easily understood the task and showed negligible pointing errors. Thus, it seems rather unlikely that the left-right hemisphere errors might be related to participants misunderstanding task instructions and demands.

Is the occurrence of left-right hemisphere errors related to general spatial abilities? Whereas Riecke (2008) observed significantly lower spatial abilities test scores for NonTurners as compared to Turners, the current study showed only non-significant trends, albeit in the same direction. Further experimentation with more participants and thus higher statistical power are needed to investigate if NonTurner behavior is indeed associated with lower overall mental spatial abilities.

How do previous point-to-origin results extend to more extreme path geometries? As participants in Riecke (2008) could not reliably disambiguate between trajectories where the lengths of the first and second segment were identical or differed by 50%, we used a much wider range of relative lengths of $s_2/s_1 = \{1/4, 1/1, 4/1\}$. Post-experimental debriefing indicated that this allowed participants to clearly disambiguate the different ratios of s_2 versus s_1. In general, previous point-to-origin results extended to those more unusual path layouts, yielding similar overall percentages of NonTurners as in previous studies and similar overall pointing response patterns.

4.3 Online Updating versus Offline/After-the-Fact Computation of Homing Direction?

If participants use online updating of the visually presented turns as is typically observed for automatic spatial updating, response times should be fairly low and not depend on the turning angle, as all processing should have been completed during the excursion path (Farrell and Robertson, 1998; Presson and Montello, 1994; Riecke et al., 2007; Rieser, 1989). Such an online strategy might be based on participants continuously keeping track of the direction to the starting position using some kind of imagined homing vector, similar to the homing vector updating that is proposed for path integration-based triangle completion in many animals including humans (Loomis et al., 1999; Müller and Wehner, 1988). Conversely, if participants use after-the-fact computation of the homing direction, on would expect response times to be (a) overall larger compared to previous studies that reported automatic spatial updating as well as (b) increase for larger turns and thus more difficult computations, especially for turning angles beyond 90° where reference frame conflicts become more pronounced.

The current data showed qualitatively different response time patterns for Turners versus NonTurners. On the one hand, Turners exhibited overall low response times of 1.07s in the practice experiment and 1.31s in the main experiment. These values are comparable to previously reported values of around 1.6s (Farrell and Robertson, 1998) and 1.2s (Riecke et al., 2007) in physical motion conditions where automatic spatial updating was observed. Moreover, Turner response times in the main experiment showed no systematic increase for larger turning angles. Together, this suggests that Turner might have used some kind of online updating strategy to perform the point-to-origin task, or a fairly efficient offline strategy, or some combination of both.

On the other hand, NonTurners showed considerably longer response times (2.34s and 2.36s for the practice and main experiment, respectively) than Turners and prior studies reporting automatic spatial updating (Farrell and Robertson, 1998; Riecke et al., 2007). Moreover, NonTurners' response times significantly increased for larger turning angles, with effect sizes η_p^2 between 28% and 46%. Both findings suggest that NonTurners might be more prone to using effortful offline, after-the-fact computation of the correct homing direction: If all computation had already been performed during the excursion path, there should be no additional computation time required for the largest and most difficult-to-update turning angles, but this is just what we found. Such after-the-fact computation might be based on some kind of mental rotations, which typically leads to a linear increase of response times with turning angle (Shepard and Metzler, 1971). Alternatively, after-the-fact computation might occur by participants using a configural strategy, for example by imagining a top-down view of the path geometry (Riecke et al., 2002; Wiener et al., 2011). The current study was not designed to disambiguate between those or other possibilities, and further studies are needed to investigate this. The data do, however, suggest that Turner and NonTurner do not only use very distinct strategies leading to qualitatively different behavior, but also systematically vary in the amount of time and cognitive resources needed to determine the homing direction. This might also be related to general differences in mental spatial abilities between Turners and NonTurners (Riecke, 2008).

As cognitive resources are scarce, and robust and effortless spatial orientation and behavior requires low effort and cognitive load, we posit that VR simulations should strive to reduce the occurrence of NonTurner strategies and other effortful and resource-intensive strategies. Thus, using relatively simple experimental paradigms such at the rapid point-to-origin use here, we can systematically investigate the perceptual and behavioral effectiveness of different stimulus and display parameters and combinations. A recent point-to-origin study in VR showed, for example, that using naturalistic stimuli can largely reduce the occurrence of NonTurner behavior, although it still occurred in 17% of participants (Sigurdarson et al., 2012). Thus combining spatial cognition research with an eye towards potential applications can not only help to systematically improve VR simulations and thus provide more effective experimental setups, but also foster a deeper understanding of the fascinating underlying processes and strategies.

References

Avraamides, M.N., Kelly, J.W.: Multiple systems of spatial memory and action. Cognitive Processing 9, 93–106 (2008)

Avraamides, M.N., Klatzky, R.L., Loomis, J.M., Golledge, R.G.: Use of cognitive versus perceptual heading during imagined locomotion depends on the response mode. Psychological Science 15(6), 403–408 (2004)

Batschelet, E.: Circular statistics in biology. Acad. Pr., London (1981)

Chance, S.S., Gaunet, F., Beall, A.C., Loomis, J.M.: Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. Presence - Teleoperators and Virtual Environments 7(2), 168–178 (1998)

Coluccia, E., Louse, G.: Gender differences in spatial orientation: A review. Journal of Environmental Psychology 24(3), 329–340 (2004)

Easton, R.D., Sholl, M.J.: Object-array structure, frames of reference, and retrieval of spatial knowledge. Journal of Experimental Psychology– Learning, Memory and Cognition 21(2), 483–500 (1995)

Etienne, A.S., Jeffery, K.J.: Path integration in mammals. Hippocampus 14(2), 180–192 (2004)

Farrell, M.J., Robertson, I.H.: Mental rotation and the automatic updating of body-centered spatial relationships. Journal of Experimental Psychology– Learning Memory and Cognition 24(1), 227–233 (1998)

Fujita, N., Loomis, J.M., Klatzky, R.L., Golledge, R.G.: A minimal representation for dead-reckoning in navigation: Updating the homing vector. Geographical Analysis 22(4), 326–335 (1990)

Gallistel, C.R.: The organization of learning. Learning, development, and conceptual change. MIT Press, Cambridge (1990)

Golledge, R.G.: Wayfinding behavior: cognitive mapping and other spatial processes. JHU Press (1999)

Gramann, K.: Embodiment of Spatial Reference Frames and Individual Differences in Reference Frame Proclivity. Spatial Cognition and Computation (2012) (online pre-print), doi:10.1080/13875868.2011.589038

Gramann, K., Muller, H.J., Eick, E.M., Schonebeck, B.: Evidence of separable spatial representations in a virtual navigation task. Journal of Experimental Psychology–Human Perception and Performance 31(6), 1199–1223 (2005)

Gramann, K., Onton, J., Riccobon, D., Mueller, H.J., Bardins, S., Makeig, S.: Human brain dynamics accompanying use of egocentric and allocentric reference frames during navigation. Journal of Cognitive Neuroscience 22(12), 2836–2849 (2010)

Gramann, K., Wing, S., Jung, T.-P., Viirre, E., Riecke, B.E.: Switching spatial reference frames for yaw and pitch navigation. Spatial Cognition and Computation 12(2-3), 159–194 (2012), doi:10.1080/13875868.2011.645176

Klatzky, R.L., Loomis, J.M., Beall, A.C., Chance, S.S., Golledge, R.G.: Spatial updating of Self-Position and orientation during real, imagined, and virtual locomotion. Psychological Science 9(4), 293–298 (1998)

Lawton, C.A., Morrin, K.A.: Gender differences in pointing accuracy in Computer-Simulated 3D mazes. Sex Roles 40(1-2), 73–92 (1999)
Loomis, J.M., Klatzky, R.L., Golledge, R.G., Philbeck, J.W.: Human navigation by path integration. In: Golledge, R.G. (ed.) Wayfinding Behavior: Cognitive Mapping and other Spatial Processes, pp. 125–151. Johns Hopkins, Baltimore (1999)
Mahmood, O., Adamo, D., Briceno, E., Moffat, S.D.: Age differences in visual path integration. Behavioural Brain Research 205(1), 88–95 (2009)
Maurer, R., Séguinot, V.: What is modelling for?– a critical review of the models of path integration. Journal of Theoretical Biology 175(4), 457–475 (1995)
May, M.: Cognitive and embodied modes of spatial imagery. Psychologische Beiträge 38(3/4), 418–434 (1996)
May, M., Klatzky, R.L.: Path integration while ignoring irrelevant movement. Journal of Experimental Psychology– Learning, Memory and Cognition 26(1), 169–186 (2000)
Müller, M., Wehner, R.: Path integration in desert ants cataglyphis fortis. Proceedings of the National Academy of Sciences 85(14), 5287–5290 (1988)
Müller, M., Wehner, R.: Path integration provides a scaffold for landmark learning in desert ants. Current Biology 20(15), 1368–1371 (2010)
Presson, C.C., Montello, D.R.: Updating after rotational and translational body movements: Coordinate structure of perspective space. Perception 23(12), 1447–1455 (1994)
Riecke, B.E., Schulte-Pelkum, J., Bülthoff, H.H.: Perceiving simulated Ego-Motions in virtual reality - comparing large screen displays with HMDs. In: Proceedings of the SPIE, San Jose, CA, USA, vol. 5666, pp. 344–355 (2005a)
Riecke, B.E.: How far can we get with just visual information? Path integration and spatial updating studies in virtual reality, Logos, Berlin, vol. 8 (2003), `http://www.logos-verlag.de/cgi-bin/buch/isbn/0440`
Riecke, B.E.: Consistent Left-Right reversals for visual path integration in virtual reality: More than a failure to update one's heading? Presence: Teleoperators and Virtual Environments 17(2), 143–175 (2008)
Riecke, B.E., Cunningham, D.W., Bülthoff, H.H.: Spatial updating in virtual reality: the sufficiency of visual information. Psychological Research 71(3), 298–313 (2007)
Riecke, B.E., Heyde, M.V.D., Bülthoff, H.H.: Visual cues can be sufficient for triggering automatic, reflexlike spatial updating. ACM Transactions on Applied Perception (TAP) 2, 183–215 (2005b); ACM ID: 1077401
Riecke, B.E., van Veen, H.A.H.C., Bülthoff, H.H.: Visual homing is possible without landmarks: a path integration study in virtual reality. Presence: Teleoperators and Virtual Environments 11, 443–473 (2002); ACM ID: 772746
Rieser, J.J.: Access to knowledge of spatial structure at novel points of observation. Journal of Experimental Psychology: Learning, Memory, and Cognition 15(6), 1157–1165 (1989)
Shepard, R.N., Metzler, J.: Mental rotation of 3-Dimensional objects. Science 171(3972), 701–703 (1971)
Sigurdarson, S., Milne, A.P., Feuereissen, D., Riecke, B.E.: Can phys-i-cal motions pre-vent dis-ori-en-ta-tion in nat-u-ral-is-tic VR? Orange County, CA, USA (2012)
Stumpf, H., Fay, E.: Schlauchfiguren - Ein Test zur Beurteilung des räumlichen Vorstellungsvermögens. Hogrefe, Göttingen (1983)
Wiener, J.M., Berthoz, A., Wolbers, T.: Dissociable cognitive mechanisms underlying human path integration. Experimental Brain Research 208(1), 61–71 (2011)
Wiener, J.M., Mallot, H.A.: Path complexity does not impair visual path integration. Spatial Cognition and Computation 6(4), 333–346 (2006)