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Moving Through Virtual Reality Without Moving?

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Abstract

Virtual Reality (VR) technology is increasingly used in spatial cognition research, as it offers high experimental control and interactivity in naturalistic multi-modal environments, something that is difficult to achieve in real-world settings. Even in the most sophisticated and costly VR systems people *do not* necessarily perceive and behave as they would in the real world. This might be related to our inability to use embodied (and thus often highly automated and effective) spatial orientation processes in VR. While real-world locomotion affords automatic and obligatory spatial updating of our self-to-surrounding relationships, such that we easily remain oriented during simple perspective changes, the same is not necessarily true in VR. This can lead to striking systematic and qualitative errors such as failures to update rotations ("Nonturner" behaviour). Here, we investigated whether rich naturalistic visual stimuli in immersive VR might be sufficient to compensate for the lack of physical motion. To this end, 24 participants performed point-to-origin tasks after visually simulated excursions along streets of varying curvature in a naturalistic virtual city. Most (21/24) participants properly updated simulated self-motions and showed only moderate regression towards mean pointing responses. 3/24 participants, however, exhibited striking "Nonturner" behaviour in that they pointed as if they did not update the visually simulated turns and their heading had not changed. This suggests that our immersive naturalistic VR stimuli were an improvement over prior optic flow stimuli, but still insufficient in eliciting obligatory spatial updating that supported correct point-to-origin responses in all participants.

Keywords: Spatial Cognition, Spatial Updating, Point-to-origin, Nonturner, Virtual Reality,

Introduction

With recent advances of computer graphics and Virtual Reality (VR) technology, we are now able to generate fairly naturalistic stimuli in immersive computer-simulated environments. Does this allow us to combine naturalism and generalizability to real-world situations with full experimental control and repeatability? That is, can we safely assume that participants in virtual environments will perceive, think, and behave similarly to the real world as long as we use the latest technology and photorealistic stimuli?

In this short paper, we focus on one area of spatial cognition where real-world and visually-simulated virtual locomotion can lead to radically different behavior and underlying strategies: point-to-origin studies (see Figure 1). In a point-to-origin task, experimenters measure the ease, speed, and accuracy with which participants can point back to the origin of locomotion after simple (typically 2-segment) excursion (Loomis et al. 1999). Various point-to-origin procedures have been employed, including visually simulated pointers (Gramann et al. 2005), physical pointers (Riecke 2008), or turning one's body to face the origin (Klatzky et al. 1998).

In a seminal study, Klatzky et al. (1998) observed strikingly different pointing behavior dependent on whether participants physically performed the rotation in-between the two outbound segments at x_1. When blindfolded participants were guided and walked along the 2-segment outbound path, turn-to-face-origin performance showed few systematic errors (as sketched in Figure 1, left), suggesting that all participants properly incorporated the turn at x_1 into their response (so-called "**Turner**" behavior (Gramann 2012; Gramann et al. 2005)).

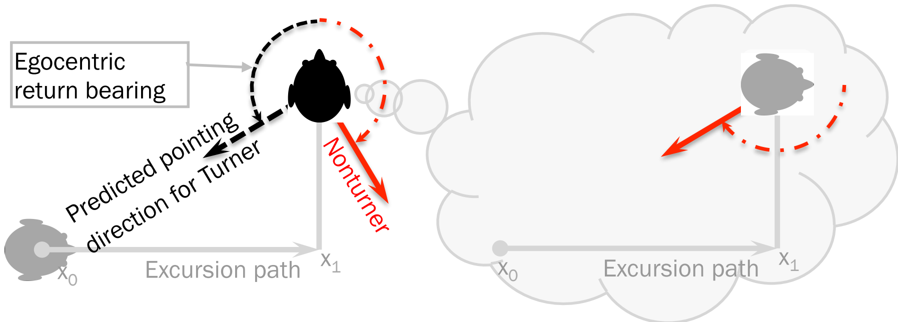

Figure 1: Schematic illustration of predicted responses for Turner and Nonturner point-to-origin behavior. Nonturner respond as if not updating/incorporating the turn and corresponding heading change at x_1 into their pointing response. That is, they respond as if still facing the original, unchanged orientation (right).

However, when participants did not physically walk and turn at x_1 but the whole excursion path was only imagined, they responded as if they failed to update/incorporate the turn at x_1 into their pointing response, as illustrated in Figure 1, right (Klatzky et al. 1998; see also Avraamides et al. 2004). Similar "**Nonturner**" behavior was observed when participants only watched somebody else walk the excursion path, or when the path was only visually simulated in a simple optic flow environment displayed via head-mounted display (again without physically moving or turning at x_1). However, when participants in a "real turn" condition saw the same optic flow simulation for the straight segments, but the turn at x_1 was also physically performed (by the experimenter rotating participants sitting on a stool), Nonturner behavior completely disappeared. All participants now showed Turner behavior and thus successfully incorporated heading changes into their subsequent turn-to-face-origin response. Later optic flow-based point-to-origin studies in VR confirmed consistent Nonturner behavior, but only in about 40-60% of participants (Gramann et al. 2012; Gramann 2012; Gramann et al. 2005; Riecke 2012; Riecke 2008) as compared to 100% in Klatzky et al. (1998). Note that some studies used initial feedback training to discourage or untrain Nonturner behavior in optic flow-based VR (e.g., Wiener and Mallot 2006).

So what is the origin of this striking Nonturner behavior that only seems to emerge when participants do not physically perform the instructed or visually simulated turns? Gramann et al. proposed that

Nonturner predominately use an allocentric strategy, whereas Turner tend to use an egocentric strategy (Gramann et al. 2012; Gramann 2012; Gramann et al. 2005). They identified different underlying neural substrates for Turner versus Nonturner behavior that support the usage of different strategies (Gramann 2012). However, Klatzky et al. (1998) argued that participants simply failed to update a perceptual representation of their heading whenever proprioceptive cues to heading changes were missing, but did not assume or find evidence for the usage of an allocentric representation.

A follow-up study demonstrated that the response mode (physical pointing versus verbal) also plays a critical role (Avraamides et al. 2004): When a verbal (and thus less embodied) response (e.g., "right, 70°") was used instead of the body-referenced turn-to-face-origin response, participants were indeed able to respond based on a successfully updated imagined/cognitive heading and thus showed Turner instead of Nonturner behavior. This might originate from a reference frame conflict between participants' imagined (or cognitive or visually simulated) heading and their physical or perceived heading: This reference frame conflict is pronounced for embodied pointing responses, but not (or to a lesser degree) for verbal (i.e., less embodied or dis-embodied) responses (Avraamides et al. 2004; Avraamides and Kelly 2008). This would explain why Nonturner behavior disappeared completely in (Klatzky et al. 1998) whenever the turn on the outbound path was physically executed.

Together, this suggest that physical rotations are necessary for enabling proper updating and thus natural and effective spatial orientation in VR, at least when only optic flow information is available. To test this hypothesis, we performed a series of experiments, and will briefly report on one of them in more detail below. For a more detailed description of the general methods used, see (Sigurdarson et al. 2012).

Experiment: Do we need Physical Rotations in VR, or can Naturalistic Cues Suffice?

Are physical rotations absolutely required to enable proper spatial updating and Turner behavior in VR simulations? Or might it be sufficient to use richer and more naturalistic visual stimuli instead of simple optic flow displays? Given the considerable extra cost and effort in allowing for physical locomotion in VR, this would not only be theoretically interesting, but could also have important practical implications.

Previous studies showed that visual cues from photorealistic real-world replica in VR can be sufficient to trigger obligatory and automatic spatial updating (Riecke et al. 2007; Riecke et al. 2005). However, these studies only investigated simulated rotations, but not translations or curvilinear paths such as the ones used in point-to-origin experiments. If naturalistic visual cues in VR were sufficient to elicit automatic and obligatory spatial updating for rotations as well as translations, *all* participants should always automatically and obligatorily have an (at least qualitatively correctly) updated perceptual representation of heading and the homing direction during simulated self-motion, that can then be used for embodied point-to-origin responses thus effectively eliminating *all* Nonturner behavior.

Methods

To tests this hypothesis, we performed a visual-only point-to-origin VR experiment with 24 naïve participants. The simulated scenery consisted of a naturalistic city environment that contained outbound paths of varying curvature {±10°, ±50°, ±90°, ±130°, and ±170°}, as illustrated in Figure 2. Participants were seated stationary, donned a head-tracked HMD (eMagin Z800), and viewed passive smooth motions along these paths before being asked to point back to the origin of locomotion using a modified joystick. Care was taken that the city environment did not contain reliable landmarks, and that participants could not see or otherwise infer the origin of locomotion from the trajectory endpoint. Compared to artificial-looking optic flow stimuli, however, the naturalistic city-scene contained ample photo-realistic detail to support spatial updating and immersion/presence.

Results and Discussion

Unexpectedly, three of the 24 participants (12.5%) showed consistent Nonturner behavior, whereas the remaining 21 participants consistently responded as Turners (Figure 2 and Figure 3). Response times for Turner and Nonturner were not significantly different ($t(22)=.255$, $p=.801$). As shown by the correlation analyses in Figure 3 (left, top inset), response times did *not* increase for larger turning angles ($p>.19$), which is one of the indicators for automatic spatial updating (Riecke et al. 2007). This suggests that the available visual cues might have been sufficient for supporting online, *automatic* spatial updating during the outbound path. However, as three participants showed consistent Nonturner behavior and thus supposedly did not update their perceived heading during the excursion path, the available naturalistic visual cues were (at least for those Nonturners) insufficient for triggering *obligatory* spatial updating – else *all* participants would have responded based on an (obligatorily) updated perceived heading, as is observed for real-world blind walking (Klatzky et al. 1998).

Note that the Nonturner-rate of 12.5% observed here is considerably lower than the 40-100% observed in optic flow-based VR (Gramann 2012; Gramann et al. 2005; Klatzky et al. 1998; Riecke 2012; Riecke 2008). This suggests a clear benefit of using naturalistic VR over simple optic flow displays, although the stimuli were not yet sufficient for completely preventing Nonturner behavior.

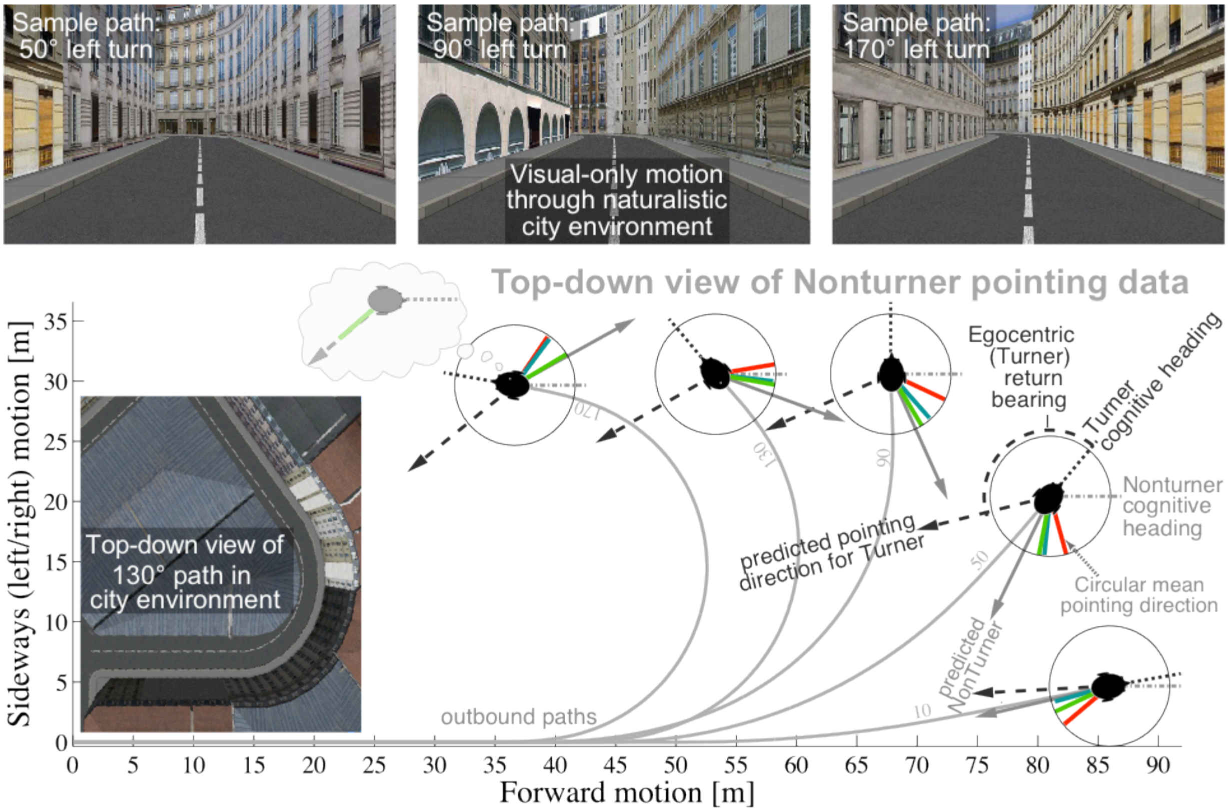

Figure 2: Excursion trajectories and circular mean pointing directions color-coded for each of the three Nonturners. Data were pooled over left and right turns.

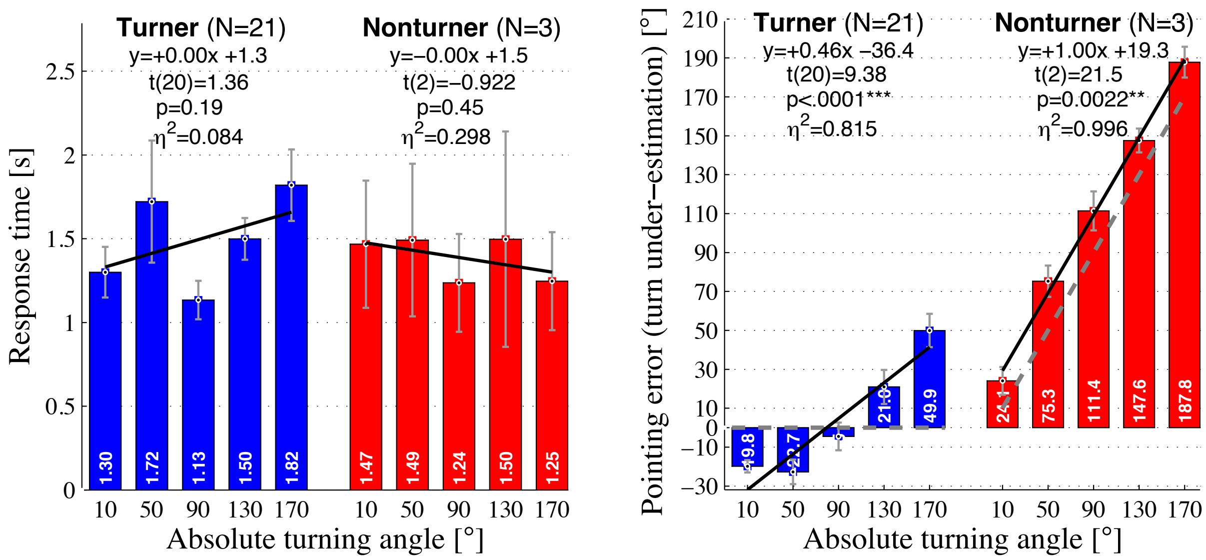

Figure 3: Response time and signed pointing errors. Whiskers depict standard errors. Note that the slope of the linear fit of the Nonturner error data (right, in black) is 1 and matches closely the predictions for Nonturners (dashed gray line). Turners showed significant regression towards mean pointing directions.

General Discussion and Conclusions

The observed Nonturner behavior and inferred failure to observe obligatory spatial updating was unexpected, as previous work has shown that immersive naturalistic VR could reliably trigger automatic and obligatory spatial updating of rotations (Riecke et al., 2005, 2007). How can this apparent contradiction be resolved?

First, the current study used combined translations and rotations, whereas Riecke et al. (2005, 2007) only studied rotations. However, as Klatzky et al. (1998) have shown, participants can easily update the translational parts of outbound paths, even when only optic flow information is available. Updating challenges arose only when rotations (but not translations) were no longer physically performed. This suggests that participants should have been easily able to update translations in the current study.

Second, Riecke et al. (2005, 2007) used a naturalistic environment that contained ample landmarks and were replica of real environments that participants were quite familiar with, whereas the current study used a naturalistic environment that participants were unfamiliar with, and that did not contain any reliable landmarks. That is, while participants in Riecke et al. (2005, 2007) could have used the known scenery and landmarks therein to remain oriented or even re-orient when teleported to a new orientation (Riecke et al. 2005), this was not possible in the current study: here, seeing a view from the endpoint of the outbound trajectories was (by design) not indicative of the homing direction. This comparison suggests that naturalistic VR is not necessarily sufficient for enabling automatic and obligatory spatial updating that supports Turner behavior unless participants can recognize views and use landmarks to remain oriented or re-orient themselves. Future studies are needed and planned to further investigate these hypothesis, though.

Are physical rotations required or at least sufficient?

Together with results from (Farrell and Robertson 1998; Klatzky et al. 1998), this suggests that whenever recognizable landmarks are missing, adding physical rotations might be necessary and should be sufficient for eliciting obligatory spatial updating that supports Turner behavior for all participants. We tested this claim by using identical procedures to the current experiment, but adding passive physical rotations in half of the trials (Sigurdarson et al. 2012). Surprisingly, however, adding physical rotations did *not* improve performance. Moreover, 17% of participants still showed clear Nonturner behavior, irrespective of the absence or presence of physical rotations. Thus, physical rotations were insufficient for reliably eliciting obligatory spatial updating that supports Turner behavior in all participants. This challenges the notion that physical rotations should support and reliably enable Turner behavior (Klatzky et al. 1998) by eliciting obligatory spatial updating (Farrell and Robertson 1998), and motivates further studies to shed light onto this both theoretically and practically relevant phenomenon.

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