

# Can Physical Motions Prevent Disorientation in Naturalistic VR?

Salvar Sigurdarson<sup>1</sup> Andrew P. Milne<sup>2</sup> Daniel Feuereissen<sup>3</sup> Bernhard E. Riecke<sup>4</sup>

Simon Fraser University

## ABSTRACT

Most virtual reality simulators have a serious flaw: Users tend to get easily lost and disoriented as they navigate. According to the prevailing opinion, this is because of the lack of actual physical motion to match the visually simulated motion: E.g., using HMD-based VR, Klatzky et al. [1] showed that participants failed to update visually simulated rotations unless they were accompanied by physical rotation of the observer, even if passive. If we use more naturalistic environments (but no salient landmarks) instead of just optic flow, would physical motion cues still be needed to prevent disorientation? To address this question, we used a paradigm inspired by Klatzky et al.: After visually displayed passive movements along curved streets in a city environment, participants were asked to point back to where they started. In half of the trials the visually displayed turns were accompanied by a matching physical rotation. Results showed that adding physical motion cues did not improve pointing performance. This suggests that physical motions might be less important to prevent disorientation if visuals are naturalistic enough. Furthermore, unexpectedly two participants consistently failed to update the visually simulated heading changes, even when they were accompanied by physical rotations. This suggests that physical motion cues do not necessarily improve spatial orientation ability in VR (by inducing obligatory spatial updating). These findings have noteworthy implications for the design of effective motion simulators.

**KEYWORDS:** virtual reality, visual cognition, spatial updating.

**INDEX TERMS:** H.5.1 [Information Interfaces and Presentation (e.g. HCI): Multimedia Information Systems—Artificial, augmented, and virtual realities; J.4 [Social and Behavioral Sciences]: Psychology.

## 1 INTRODUCTION

As we move around our environment, the relationship between our bodies and our surroundings changes constantly. To stay oriented, we need to continuously recalculate the relative positions and directions of objects around us. This critical ability to perceive the world as stable relies on a process called ‘automatic spatial updating’ [2-4]. It is a process that updates our internal representation of the environment according to movement cues from our visual, vestibular and proprioceptive systems.

Fortunately, these recalculations take little conscious effort, even with little or no visual information [2-4]. You can try this out yourself: Close your eyes, walk towards the nearest door, touch it and return to where you were before. You are able to navigate the room with your eyes closed because you automatically update your mental model of the room as you move and turn. In many situations, spatial updating is ‘obligatory’ in the sense that it is hard to suppress [5-7].

However, the process of automatic spatial updating is often ab-

sent in virtual reality simulators. This is one reason that users tend to get disoriented quickly as they move around in virtual environments, especially if they cannot rely on any salient landmarks to stay oriented [8]. That is, automatic spatial updating does not seem to be triggered as easily in VR as in the real world. Instead, users often need to resort to more cognitively demanding strategies to stay oriented. This can be problematic for implementations of VR, especially when cognitive load is already high. For example, a flight simulator where users need to spend additional cognitive resources for remaining oriented will not be very useful.

Why can we update our internal representation of the environment as we move around in the real world, yet have so much trouble doing so in virtual worlds? Research has shown that spatial updating in virtual environments can be facilitated if people are allowed to physically perform the simulated movements, for example by walking or turning [1], [8-10]. Active control of movement does not seem to be required [1]. When physical motion cues are missing, spatial updating has been found to be impaired [3], [4], [10]. This has resulted in the prevailing notion that physical motion cues are required to enable automatic spatial updating during movement, and that visual cues alone are not enough.

However, Riecke et al. challenged this notion in two spatial updating studies [6], [7], suggesting that the apparent inadequacy of visual cues might be largely due to inadequacies of the visual simulation, namely a lack of naturalistic scenes in sufficient detail, field of view, and other display factors. Using detailed photo-realistic replica of real scenes rather than optic flow (a moving visual field without salient landmarks, like a star field), they found that visual information alone could in fact suffice to elicit automatic and obligatory spatial updating during rotations in a virtual environment. However, they did not test translations in their studies. It remains to be determined if or to what degree naturalistic visual cues might afford automatic spatial updating for motions including both rotations and translations.

The purpose of this study is to close this gap by further investigating the contribution of physical motion cues to automatic spatial updating. When moving along a path in a virtual city with naturalistic and highly structured visuals, are physical rotations still needed to enable automatic spatial updating, or can the visuals alone suffice?

To this end, we use a virtual spatial updating task based on an established point-to-origin paradigm [11], [12]. Participants moved passively along streets of varying curvature, at the end of which they were asked to point back to the origin of the path using a modified joystick. To implement physical rotations, we seated participants on a software-controlled rotating chair.

We purposefully did not include any salient landmarks. This was so that participants could not solely use piloting (landmark-based navigation) to perform the task, but had to incorporate rotational and translational cues (path integration). Therefore, our study did not require participants to establish a “cognitive map”, although some might have [13]. We hypothesized as follows:

**H1:** Based on previous blind walking and optic flow studies [2], [4], [8], adding physical motion cues should enable automatic spatial updating. This in turn should yield improved point-to-origin performance (unless the visual cues were already sufficient to enable automatic spatial updating). This would indicate that physical motions are necessary for successful spatial orientation in

<sup>1</sup> e-mail: ssigurda@sfu.ca

<sup>2</sup> e-mail: apmilne@sfu.ca

<sup>3</sup> e-mail: dfeuerei@sfu.ca

<sup>4</sup> e-mail: ber1@sfu.ca

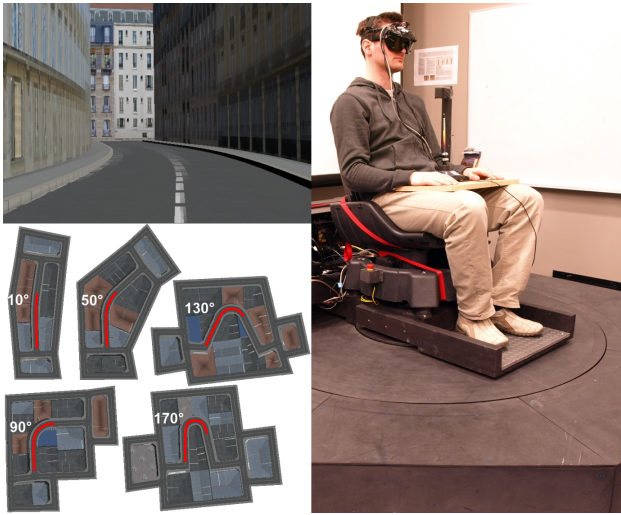


Figure 1: The experimental setup. Participants sat in a rotating chair wearing an HMD (right), placed in a virtual city (left).

VR, even if naturalistic visuals are used. Conversely, should performance not improve when adding physical motions, we would conclude that either the visual environment was sufficient to fully trigger automatic spatial updating, or the physical cues failed to trigger spatial updating.

**H2:** Based on research on imagined perspectives switches we expect larger pointing errors for increasing turning angles [1], [12], [14].

**H3:** If spatial updating is automatic, no additional processing time should be needed at the end of the motion, as the mental representation was already automatically updated during the motion [2], [4]. That is, response times should show little if any increase with turning angle. Conversely, should the response time clearly increase with turning angle we could infer that spatial updating was not fully automatic.

Our last three hypotheses refer to a phenomenon described by Klatzky et al. [1], and later corroborated by Gramann et al. [11] & Riecke [12] in optic flow-based VR studies:

Using a turn-to-face-origin task after two-segment excursions, Klatzky et al. observed that participants responded correctly whenever the rotation between the first and second segment was physically performed (even when translations were not physically executed). However, in conditions where rotations were only verbally described or displayed via optic flow in a head-mounted display (HMD), participants responded as if still facing the original direction. That is, they responded as if their mental spatial representation used for pointing was not properly updated. Participant that showed such qualitative errors have been termed “nonturners” by Gramann et al [11], as compared to “turners” that correctly update the turns. This has several predictions:

**H4:** If the VISUAL ONLY TURN conditions are sufficient to trigger obligatory spatial updating, rotations should always be updated during those conditions. That is, we should only observe turner behavior. Hence, any observation of consistent nonturner behavior would indicate that the visual cues alone were insufficient to obligatorily trigger spatial updating, at least for those participants.

**H5:** Similarly, if added physical rotations trigger obligatory spatial updating as predicted by [1], [3], [4], we should not observe any failures to update rotations during those conditions. That is, we should only observe turner behavior.

**H6:** Observing less nonturner behavior in the REAL TURN condition would indicate that adding physical rotation cues leads to more obligatory spatial updating.

## 2 METHODS

### 2.1 Participants

A total of 12 Simon Fraser University undergraduate and graduate students (4 female) voluntarily participated in all parts of this study. They either received monetary compensation at standard rates, or course credit. Participant ages ranged from 18 to 33 years (mean = 22.5 years). All participants had normal or corrected-to-normal vision, reported no history of motion-sickness and were naïve to the purposes of the experiment. The study was approved by the university’s ethics board. Informed consent forms were obtained from each participant before the experiment.

### 2.2 Stimuli and Apparatus

The virtual environment was displayed non-stereoscopically using an eMagin Z800 3D Visor HMD at a resolution of  $800 \times 600$  pixels and a field of view of  $32^\circ \times 24^\circ$  at 60 Hz. Head movements were tracked via a Polhemus 6 degree-of-freedom motion tracker. Participants wore active noise-cancelling headphones and a blindfold mask over the HMD to exclude all auditory and visual cues from the surrounding lab.

Participants were seated on a chair mounted centrally on a  $2 \times 2$  m computer-controlled motion simulator, as illustrated in Figure 1 (see <http://iSpaceLab.com/iSpaceMecha>). The virtual environment was created using Procedural’s CityEngine 3D modeler and rendered using Worldvz Vizard software. It consisted of a three-dimensional model of a city environment that contained ten individual curved street segments, surrounded with buildings (see Figure 1). Each street segment was designed to have a 45m long straight portion followed by a 40m long curve of  $10^\circ$ ,  $50^\circ$ ,  $90^\circ$ ,  $130^\circ$  and  $170^\circ$  in either direction. Although naturalistic, the virtual scene did not contain any salient landmarks that participants could have used for determining where they were relative to the starting point.

### 2.3 Procedure

Each trial involved a passive motion phase and a pointing phase. The motion phase consisted of a translation and rotation along one curved street segment within the virtual environment (3 m/s maximum translational velocity with a short acceleration and deceleration phase,  $40^\circ/\text{s}$  maximum rotational velocity with an acceleration of  $50^\circ/\text{s}^2$ , which was noticeably above detection threshold). Upon arriving at the end of the trajectory, participants were asked to point “as quickly and accurately as possible” to the origin of the movement as if they had physically traveled it. Participants pointed with a modified Logitech Attack 3 joystick that was mounted on a wooden board and positioned on the participant’s lap.

Two movement conditions were compared: In the REAL TURN condition, participants rotated on the motion simulator as their viewpoint rotated in the virtual environment. In the VISUAL ONLY TURN condition, participants did not physically rotate. A real-world practice phase was used to ensure that they understood the procedure and could consistently point with at least  $20^\circ$  accuracy to a visible target. There was no visual indication of pointing response, so participants had to rely on proprioceptive and haptic cues to indicate in which direction they were pointing.

Participants never received any feedback on pointing accuracy. This was done to prevent participants from using cognitive strategies or recalibration for the pointing task, as previous studies have shown that when given unlimited response time and feedback participants can perform point-to-origin tasks relatively well [14].

### 2.4 Experimental Design

We used a  $2$  (movement condition: REAL TURN, VISUAL ONLY TURN)  $\times 2$  (turning direction: left, right)  $\times 5$  (turning angle:  $10^\circ$ ,

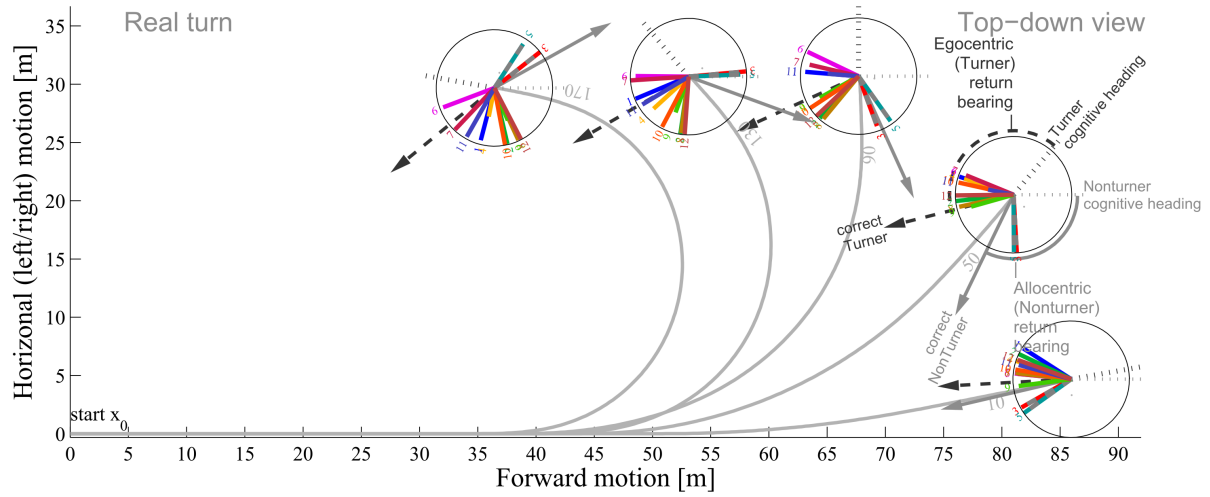


Figure 2: Path trajectories and circular mean pointing directions in Real Turn conditions. Each colored line represents one participant.

50°, 90°, 130°, 170°) within-participant experimental design. The main experiment had 3 sessions, consisting of 20 trials each (10 for each of the 2 movement conditions in balanced order). Movement conditions were blocked within each session, while the virtual turning direction and angle were randomized. The experiment took less than one hour overall.

### 3 RESULTS AND DISCUSSION

Pointing data were pooled over the two turning directions (which were not the focus of the study), and analyzed using two-way repeated measures ANOVAs. Greenhouse-Geisser correction was applied where needed. Dependent measures were response time, absolute pointing error and signed pointing error. The factors were **movement condition** and **turning angle**.

When analyzing pointing data, we observed that two participants showed consistent nonturner behavior, as they always pointed as if they had not incorporated any rotations at all. To prevent these qualitatively different responses from distorting the analysis of remaining participants, we separated them from the main group during analysis.

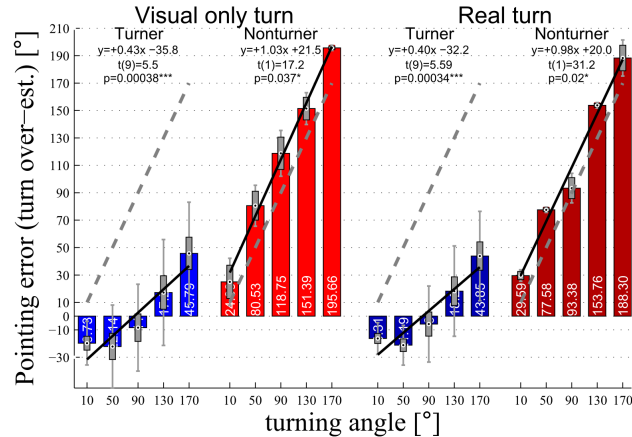


Figure 3: Signed pointing errors for each turn condition.

**H1: Do physical motion cues always enable automatic spatial updating?** The results, unexpectedly, showed no significant effect of turning condition on absolute pointing error,  $F(1, 9) = .123$ ,  $p < .734$ , signed pointing error,  $F(1, 9) = .130$ ,  $p < .727$  or response time,  $F(1, 9) = 1.645$ ,  $p < .232$ . That is, partici-

pants were no better spatially oriented when they received physical motion cues. According to our hypothesis we conclude that either the visual environment was sufficient to fully enable automatic spatial updating in all conditions, or that physical cues failed to enable automatic spatial updating. For whatever underlying reasons, adding physical motion cues to the current setup and procedure showed no benefits, which is noteworthy for VR simulation.

#### H2: Do pointing errors increase for larger turns?

Turning angle significantly affected absolute pointing error,  $F(1.526, 13.738) = 5.193$ ,  $p < .028$ . Although absolute pointing errors generally increased with increasing turning angles, Bonferroni-corrected post hoc tests showed no significant pairwise difference. This increase in pointing error is potentially due to accumulating path integration errors and/or higher task difficulty.

#### H3: Does pointing take longer for larger angles?

Response time was on average 1.35s and was significantly affected by turning angle,  $F(1, 9) = 2.693$ ,  $p < .046$ . However, correlations did not reach significance ( $t(9) = 1.6$ ,  $p = 0.14$  for REAL TURN, and  $t(9) = 0.99$ ,  $p = 0.35$  for VISUAL ONLY TURN), suggesting the ANOVA effects were spurious. Thus, on average, participants pointed neither faster nor slower as the turning angle increased. As this is one of the indicators of automatic spatial updating [6], this suggests that the visual cues were sufficient for enabling automatic spatial updating, irrespective of whether they were accompanied by matching physical rotations.

#### H4: Do we observe VISUAL ONLY TURN nonturners?

As mentioned above, careful analysis of all the experimental conditions revealed that 2 of the 12 participants (#3 and #5, see Figure 2) consistently exhibited non-turning behavior throughout all trials in the VISUAL ONLY TURN condition. This observation of two consistent nonturners indicates that the visual cues alone were insufficient to obligatorily trigger spatial updating, at least for those two participants.

#### H5: Do we observe REAL TURN nonturners?

Based on [2] we expected that adding physical rotations should yield obligatory spatial updating. Thus, we should not have observed any nonturners in the REAL TURN condition. Surprisingly, however, we again observed consistent nonturning behavior for the same two participants, even when they physically rotated. Note that both nonturners exhibited this behavior from the initial trials, which were REAL TURN condition in their case. Hence, we can

exclude the possibility that they transferred their nonturner strategy from the visual-only condition.

**H6: Do physical motion cues obligatorily trigger spatial updating?** Opposite to what we expected, nonturning behavior was not reduced when physical rotations were added. This suggests that spatial updating was by no means more obligatory in the REAL TURN conditions.

#### 4 CONCLUSION

The ultimate goal of this research is to enable spatial orientation in virtual environments that is as effective as in the real world. One of the factors contributing to disorientation in VR is a lack of automatic and obligatory spatial updating. Previous research has suggested that physical motion cues are necessary to address this problem. However, Riecke et al. [6], [7] found that visual cues alone can be sufficient to trigger spatial updating provided that they are naturalistic. In the study performed by Riecke et al., however, participants were only tested with rotational movements, but not translations or curved motions. This study extends those results by testing users' spatial orientation after travelling along curved paths that include translations and rotations.

Our results suggest that naturalistic visuals may under certain conditions reduce or even eliminate the need for physical rotation cues, but more research is needed. We are currently investigating how systematic degradation of the visual stimulus might affect these results. This will allow us to test if there is indeed a "winner takes all" effect, where physical motion cues do not further improve performance if the visuals are rich and naturalistic enough.

Although the current study did not include a pure optic flow condition, comparing our results with the most similar prior study [12] shows smaller absolute pointing errors (34.9° vs. 50.8°) and smaller circular standard deviations (10.2° vs. 31.4°) for the naturalistic city environment used in the current study, corroborating [6], [7]. However, there are additional methodological differences between the studies, such that further experimentation is needed to draw any firm conclusions.

Unexpectedly, we observed two participants that exhibited nonturner behavior, that is, they responded as if they were still facing the original direction even though they clearly were aware of the actual path. This is noteworthy for two reasons: First of all, previous research found greater numbers of nonturners in visual only conditions (Riecke et al. 40% [12], Gramann et al. 50% [11], Klatzky et al. 100% [1]). In this study the percentage of nonturners was however considerably smaller (17%). We posit that this might, at least in part, be explained by the more naturalistic visual cues used in the current study, even though they contained no salient landmarks. This is promising for VR simulations in that it suggests that by further increasing display quality we might be able to fully prevent nonturner behavior, which is an important step towards effective yet affordable VR.

Secondly, it is interesting that the nonturner participants in this study continued to exhibit the same behavior even when additional physical motion cues were provided. To the best of our knowledge, this is the first time that nonturner behavior was reported despite physical motion and naturalistic visuals. This contradicts previous research which suggests that physical motion cues are sufficient to trigger obligatory spatial updating (e.g., [2]). There are of course differences to prior studies that could have contributed. For example, prior studies that observed automatic spatial updating often alternated translations and rotations [1-5], [9], [10], whereas we combined them to yield a smoothly curved path. More research is needed to investigate this phenomenon.

A potential limitation of the current study is the possibility that adding physical rotation cues did not lead to a significant increase in performance because the task was simply too easy. This is un-

likely, given the substantial error in pointing responses, and the fact that performance decreased significantly for larger turning angles. Another possible limitation is that participants that exhibited nonturner behavior were simply not executing the task as instructed. However, these participants systematically incorporated the path geometry into their responses but responded from their original heading. This can be seen in Figure 2.

Systematically investigating the conditions under which automatic and obligatory spatial updating occur will not only deepen our understanding of human spatial cognition but can also guide the design of more effective VR simulations. Our current paradigm of measuring the occurrence of turner/nonturner behavior along with performance in a point-to-origin experiment is a step towards that goal. We will continue to refine our approach in future research.

#### Acknowledgements

Support: NSERC 611547 & 613337, Simon Fraser University.

#### REFERENCES

- [1] R. L. Klatzky, J. M. Loomis, A. C. Beall, S. S. Chance, and R. G. Golledge, "Spatial updating of self-position and orientation during real, imagined, and virtual locomotion," *Psychological science*, vol. 9, no. 4, p. 293, 1998.
- [2] M. J. Farrell and I. H. Robertson, "Mental rotation and automatic updating of body-centered spatial relationships," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, vol. 24, no. 1, pp. 227-233, 1998.
- [3] C. C. Presson and D. R. Montello, "Updating after rotational and translational body movements: Coordinate structure of perspective space," *Perception*, vol. 23, pp. 1447-1455, 1994.
- [4] J. J. Rieser, "Access to knowledge of spatial structure at novel points of observation," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, vol. 15, no. 6, p. 1157, 1989.
- [5] M. May and R. L. Klatzky, "Path integration while ignoring irrelevant movement," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, vol. 26, no. 1, pp. 169-186, 2000.
- [6] B. E. Riecke, D. W. Cunningham, and H. H. Bühlhoff, "Spatial updating in virtual reality: the sufficiency of visual information," *Psychological research*, vol. 71, no. 3, pp. 298-313, May. 2007.
- [7] B. E. Riecke, M. V. D. Heyde, and H. H. Bühlhoff, "Visual cues can be sufficient for triggering automatic, reflexlike spatial updating," *ACM Transactions on Applied Perception*, vol. 2, no. 3, pp. 183-215, 2006.
- [8] R. Ruddle and S. Lessels, "For efficient navigational search, humans require full physical movement, but not a rich visual scene," *Psychological science*, vol. 17, no. 6, pp. 460-5, Jun. 2006.
- [9] S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis, "Locomotion Mode Affects the Updating of Objects Encountered During Travel: The Contribution of Vestibular and Proprioceptive Inputs to Path Integration," *Presence: Teleoperators & Virtual Environments*, vol. 7, no. 2, pp. 168-178, Apr. 1998.
- [10] M. Wraga, S. H. Creem-Regehr, and D. R. Proffitt, "Spatial updating of virtual displays during self- and display rotation," *Memory & cognition*, vol. 32, no. 3, pp. 399-415, Apr. 2004.
- [11] K. Gramann, H. J. Müller, E.-M. Eick, and B. Schönebeck, "Evidence of separable spatial representations in a virtual navigation task," *Journal of experimental psychology: Human perception and performance*, vol. 31, no. 6, pp. 1199-223, Dec. 2005.
- [12] B. E. Riecke, "Consistent Left-Right Reversals for Visual Path Integration in Virtual Reality: More than a Failure to Update One's Heading?," *Presence: Teleoperators & Virtual Environments*, vol. 17, no. 2, pp. 143-175, Apr. 2008.
- [13] T. Ishikawa and D. R. Montello, "Spatial knowledge acquisition from direct experience in the environment," *Cognitive psychology*, vol. 52, no. 2, pp. 93-129, Mar. 2006.
- [14] J. M. Wiener and H. A. Mallot, "Path complexity does not impair visual path integration," *Spatial Cognition & Computation*, vol. 6, no. 4, pp. 333-346, 2006.