International Cartographic Association
Association Cartographique Internationale

Take Me Home: How Locomotion Methods in Virtual Reality Affect Path Integration Performance

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Keywords: Virtual Reality (VR), Virtual Locomotion, Path Integration, Spatial Cognition

Abstract:
Virtual reality (VR) enables controlled and replicable investigation of cartographic and spatial-cognitive processes. A key challenge in this context is selecting the appropriate (virtual) locomotion method. Three of the most prominent VR-based locomotion methods are room-scale VR, continuous controller-based locomotion and teleportation. Room-scale VR mirrors real-world movements into the virtual environment. This limits the traversable virtual area to the dimensions of the available real-world space. Controller-based continuous artificial locomotion does not limit the traversable virtual area, but the absence of corresponding proprioceptive sensory input can cause VR sickness. Teleportation reduces this risk of VR sickness by using discontinuous jumps as a means of movement, but at the cost of interrupting the visual flow (Boletsis and Cedergren 2019). Since spatial perception depends on the integration of visual and proprioceptive self-motion cues (Campos et al. 2012), locomotion methods may directly influence underlying neural navigation mechanisms. Grid cell-like representations play a central role here, encoding an internal metric reference system in the human brain through hexagonal activity patterns (Hafting et al. 2005). Limited self-motion cues could lead to a temporary destabilization or remapping of these grid cell activity patterns (Peng et al. 2025; Fyhn et al. 2007). Therefore, we hypothesize that teleportation and controller-based locomotion impair path integration (PI) performance compared to room-scale VR due to reduced or disrupted self-motion cues.

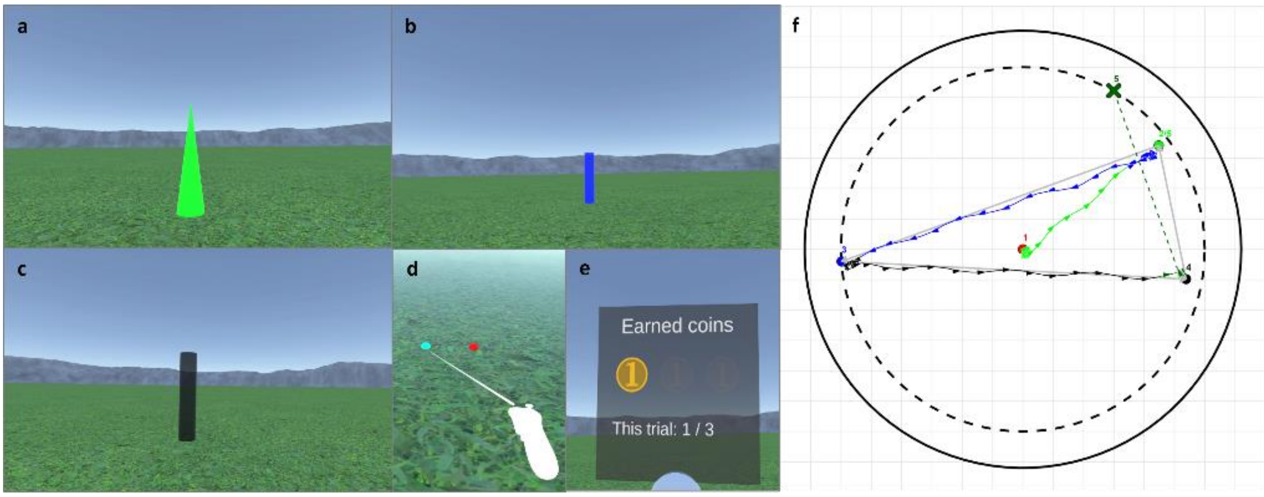

Figure 1. Insights on the virtual PI task from the participant's perspective, showing the task relevant PI-positions (a green cone as the PI target position and two additional PI positions represented by blue and black cylinders) as well as the controller-feature to log in the estimated position with the corresponding coin-feedback canvas throughout the trial (a-e). Every 2 seconds, movement data were recorded for each PI trial and visualized to identify datasets for exclusion due to notable strategies or technical issues (f).

To test this hypothesis, we examined the influence of room-scale VR, continuous artificial locomotion and teleportation on PI performance in VR using the Meta Quest Pro head-mounted display. In a virtual environment containing no local reference points, 35 participants from the student community (16 females, 19 males; 20–42 years, M = 26.06, SD = 5.02;

Abstracts of the International Cartographic Association, 12, 104, 2026
European Cartographic Conference – EuroCarto 2026, 8–11 September 2026, Brno, Czech Republic.
https://doi.org/10.5194/ica-abs-12-104-2026

M_{female} = 25.88, SD_{female} = 5.90; M_{male} = 26.21, SD_{male} = 4.30) navigated to three PI positions (Figure 1a– c).The virtual environment comprised a grass-like plane enclosed by a mountain range without dominant reference points rendered at infinity. PI positions were defined by different colored cylinders and a cone serving as a target location. A total of nine PI patterns were generated using a custom PI-pattern generator developed with RStudio (O'Meara & Korte, 2026) and presented to each participant in a randomized order after a short familiarization phase of one training trial per locomotion method. After reaching the third PI position, participants used their controllers to point at the first PI position they had to memorize as accurately as possible (Figure 1 d). Depending on the participant's PI performance, calculated as the Euclidean distance (in meters) between actual and estimated positions, they received zero to three coins as performance feedback at the end of the trial (Figure 1 e). Statistical analyses revealed significant differences depending on the locomotion method used, which were presented in a pseudorandomized order across participants. For distance error, a Friedman test revealed a significant effect of locomotion method ($\chi^2(2) = 9.31$, $p = 0.0095$). Compared to teleportation, distance errors were significantly lower when room-scale VR locomotion was used ($W = 153, p_{Holm} = 0.0245$). Further pairwise comparisons revealed differences between room-scale VR and continuous movement regarding the distance error variable, which, after applying Holm correction, remained at a trending level ($W = 443, p_{Holm} = 0.0735$). A similar trend in distance error was also observed between the two controller-based methods ($W = 212, p_{Holm} = 0.0932$). For angular errors, a Friedman test also revealed a significant effect ($\chi^2(2) = 9.83, p = 0.0073$). However, the effect between room-scale VR and teleportation, after Holm correction, was at a trending level ($W = 179, p_{Holm} = 0.0794$). Taken together, room-scale VR yielded the lowest PI errors, whereas teleportation resulted in the poorest performance. The latter may be due to the spatial relocation without visual flow cues, potentially triggering remapping processes of the grid cell firing patterns, which may have impaired spatial orientation. While teleportation has previously been found to be advantageous for simple distance estimations along straight paths if participants are provided with a distance estimation training (Keil et al. 2021), the results suggest that optic flow cues and proprioceptive feedback may affect performance in more complex and natural spatial tasks such as PI. Overall, the study highlights the importance of selecting locomotion methods matching the spatial demands of VR-based studies.

Acknowledgements

Funded by the European Union (ERC, InnerMap, 101096046). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.
We would like to thank our student assistants on the cartography team for conducting the tests for this study.

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https://doi.org/10.5194/ica-abs-12-104-2026