Long-Term Landmark and Route Memory Retention Acquired in a Real-World Map-Aided Navigation Task

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Abstract

The visualization of landmarks in mobile maps has become a popular countermeasure to the negative effect navigation aids have on spatial learning. Landmarks are salient environmental cues that serve as cognitive anchors during navigation, facilitating spatial memory formation and long-term retention. However, longitudinal studies assessing long-term spatial memory retention acquired during mobile map-assisted navigation in the real world and what role visualized landmarks play in this context are still scarce. We report on a longitudinal study to assess long-term spatial memory retention of wayfinders who, two years prior, navigated only once a real-world route prescribed with a mobile map aid enriched with visually salient task-relevant landmarks. We report preliminary results on their long-term memory retention of acquired landmark and route knowledge. We found that participants retained meaningful long-term landmark and route knowledge over the two-year study period. While landmark knowledge decreased over the test-retest sessions, gained route knowledge was unaffected. These ecologically valid results contribute to a better understanding of spatial memory formation and long-term retention after one route exposure through a real-world environment, aided by a mobile map enriched with salient landmarks.

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Supplementary Material *Collection (study's preregistration report, data, and R analyses code)*: https://doi.org/10.17605/osf.io/z93ak

1 Introduction

Imagine your friends invite you to a bar where you met them once a couple of years back. To reach this unfamiliar destination back then, you relied on your trusted navigation aid. This time, you decide to put your spatial memory to the test since you have already traversed the same route once. You must now identify salient environmental features and match them

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with the same features from your prior experience with this route that are encoded in your long-term spatial memory in order to reach the destination [19]. How successful would you be? How much of the spatial knowledge acquired during the previous exposure to the route is stored in your long-term spatial memory [24, 15], and can you recognize the environmental cues and the associated turning directions in your upcoming navigation quest?

In our spatially enabled society, we rely on ubiquitous mobile map aids to guide us to our intended destination [3], especially in unfamiliar environments. However, previous research has demonstrated that the habitual use and reliance on navigation aids impairs wayfinders' short- and long-term spatial memories [3, 14]. The negative effects of map aids are attributed to dividing wayfinders' visual attention between the environment and the map display [7] and entering wayfinders into a passive navigation state where the task is off-loaded to the map aid [1, 14]. Furthermore, the current map aids do not present wayfinders with visually salient landmark information [16] despite the well-established role of landmarks as cognitive anchors for human navigation and spatial memory formations [5, 22]. Landmarks are salient environmental cues that guide wayfinders' attention to task-relevant information during navigation, help them stay oriented in the surrounding environment, and are important for building a long-term representation of the layout of the traversed environment [22, 5].

While there is a plethora of research investigating the role of brain regions for storing and retrieving long-term spatial memories (see reviews by [28, 22]), longitudinal studies investigating wayfinders' long-term spatial memory retention after real-world navigation aided by mobile maps are still scarce [2].

The present study

In the initial study, participants were asked to navigate from a pre-defined starting location to the end destination of a real-world route approximately 1 km long that was prescribed to them on a mobile map. Ten task-relevant landmarks located at decision point intersections were saliently displayed on the mobile map as either abstract 3D or realistic 3D symbols. The study used a within-subject design with the landmark visualization style as the independent variable. That is, all participants were exposed to the same route, but the order of the landmark visualization style was counterbalanced across participants. Specifically, half of the participants navigated the route with the first five landmarks depicted as either abstract or realistic symbols. As dependent variables, we used spatial knowledge tests and eye-tracking and electroencephalography recordings (see results at [16, 12, 11]).

In the present longitudinal study, we set out to investigate long-term spatial memory retention of participants who had, two years prior, navigated a real-world route prescribed with a mobile map aid that was enriched with visually salient landmarks. Specifically, we sought to answer the following research question: *How well do participants retain landmark and route knowledge in spatial memory that was acquired two years ago after one single exposure to a route in the real world during a map-assisted navigation task?*

2 Methods

2.1 Participants

All 46 participants joining the first navigation study were invited back for the present longitudinal study. We were able to recruit 25 participants (12 females; M age = 29.84 ±5.27 years) to return for the present study. The mean delay between the study sessions was 725.2 ±15.77 days, and all the participants recalled completing the initial navigation study. When presented with a map of the study area and the predefined route after completing all tests, 19 participants (76%) reported that they had not visited the navigated route since the initial study. The present study was approved by the Ethics Committee of the University of Zurich (No. 23.10.05). Participants provided written informed consent before the start of the study and were compensated with CHF 20.

2.2 Experimental design

We administered the same tests of spatial knowledge as in the initial experiment. The key difference was that participants were not given any opportunity to re-experience the route, so all of their responses were based on the memory from the initial navigation experience. The primary independent variable was the test session (initial test vs. follow-up retest). Additionally, the initial study manipulated the visualization style of landmarks to be realistic 3D or abstract 3D symbols on the map, and we retained this variable for analysis in the present study. We used multiple dependent variables to assess participants' long-term spatial memory retention. This included landmark recognition, recall of route directions associated with landmarks, landmark-free reconstruction of order, and direction and distance estimation between landmark pairs. We also took new measurements to be used as predictors of long-term spatial memory: self-reported spatial abilities using a standardized questionnaire [23], perspective-taking and spatial orientation ability test (PTSOT; [10]), and GPS reliance and dependency scale using a modified version of the McGill GPS questionnaire [3]. The present paper focuses on landmark and route knowledge retention (see 2.3). The other measures will be analyzed in future work and are mentioned in the procedure section (see 2.4) for context and replicability purposes.

2.3 Questionnaire measures

The landmark knowledge questionnaire assessed long-term retention of landmark knowledge. Participants were presented – in random order – with 30 images of buildings and were asked first to indicate whether they recognized having seen the buildings as being from the traversed route or not. If recognized, they were asked to indicate whether the building was depicted on the mobile map in 3D. There were 10 task-relevant landmarks (REL) from intersections where a navigation decision was required that were depicted on the map, 10 task-irrelevant landmarks (IRL) encountered along the route where no change of direction was required and were not depicted on the map, and 10 additional novel landmarks (NOV) from elsewhere in the study area that were not encountered along the route nor featured on the map.

The route knowledge questionnaire assessed long-term retention of route knowledge. Participants were shown – in random order – the 10 images of REL landmarks and were asked to recall the turning direction at the building (i.e., straight, left, or right).

2.4 Procedure

Participants were welcomed to an office that served as a testing laboratory. After providing informed consent, they were instructed how to complete a set of questionnaires and test instruments in the following order: demographic data and self-reported spatial abilities, GPS reliance and dependency, PTSOT, landmark knowledge, route knowledge, landmark-free reconstruction of order, direction and distance estimation between landmark pairs, and self-report whether they have returned to the study area since that initial navigation study.

2.5 Data analyses

To assess participants' long-term retention of acquired landmark knowledge, we employed signal detection theory (SDT; [29]) using the *psycho* package [21] in R (v.4.2.2). Specifically, we used the *discriminability index d prime (d')* to assess participants' ability to distinguish present landmarks from distractors, computed as *d' = z(hit) – z(false alarm)*. We also used the *criterion location (c)* to assess participants' response bias, computed as *c = -0.5 * [z(hit) + z(false alarm)]*. We used SDT to run a two-fold analysis. First, we analyzed long-term recognition memory for landmarks present in the environment (i.e., REL and IRL) versus those that are not in the environment (i.e., NOL) during the initial navigation task. Second, we analyzed long-term recognition memory for landmarks present in the environment and depicted on the mobile map (i.e., REL) versus landmarks present only in the environment (i.e., IRL). We used the recall accuracy of turning directions (in percent) to assess participants' long-term retention of route knowledge.

We employed one-tailed t-tests on each condition to assess whether participants' long-term landmark – for the landmarks seen in the environment and on the mobile map – and route knowledge memory retention was greater than chance, specifically d' = 0 and route accuracy = 33.3%. We adjusted our alpha level to account for multiple comparisons using the Bonferroni method and accepted significance at $p < .0083$ (significance threshold .05/6 chance performance tests). We also ran two-tailed t-tests to assess whether participants' long-term landmark memory on each condition was lower or higher than zero – no bias. Negative values indicate a bias toward *"yes"* and positive values a bias toward *"no"* responses [29]. Using the Bonferroni method to adjust the alpha level for multiple comparisons, we accepted significance at $p < .013$ (.05/4 tests per landmarks seen in the environment and mobile map across the conditions). Additionally, we used repeated-measure ANOVAs within the landmark visualization condition and test session to assess long-term landmark and route memory retention, including landmark response bias.

3 Results

3.1 Landmark memory retention

Landmarks seen in the environment. Participants' long-term memory retention of the landmarks seen in the environment was above chance for both the abstract ($t(24) = 5.21$, $p < .001$) and realistic ($t(24) = 4.30$, $p < .001$) conditions (Figure 1). The repeated measure ANOVA revealed a significant effect of the test session on landmark memory ($F(1, 24) = 19.82$, $p < .001$). However, there was no significant effect of the visualization condition ($F(1, 24) = 0.016$, $p = .902$) and no interaction with the test session ($F(1, 24) = 0.598$, $p = .447$). These results show that long-term landmark memory decreases over the test sessions, regardless of the conditions (Figure 1). Participants' retest response bias was not different from zero for the abstract ($t(24) = 1.15$, $p = .261$) and realistic ($t(24) = 1.91$, $p = .068$) conditions. The ANOVA did not reveal main effects of test session ($F(1, 24) = 1.974$, $p = .173$) or condition ($F(1, 24) = 0.008$, $p = .928$), nor an interaction effect ($F(1, 24) = 0.314$, $p = .580$) on response bias.

Landmarks seen on the mobile map. Participants' long-term memory retention of the landmarks seen on the mobile was above chance for the abstract ($t(24) = 5.37$, $p < .001$) and the realistic ($t(24) = 3.83$, $p < .001$) conditions (Figure 2). The ANOVA results revealed a significant main effect of the test session ($F(1, 24) = 45.66$, $p < .001$) but no main effect of the visualization condition ($F(1, 24) = 0.936$, $p = .343$) and no interaction effect ($F(1,

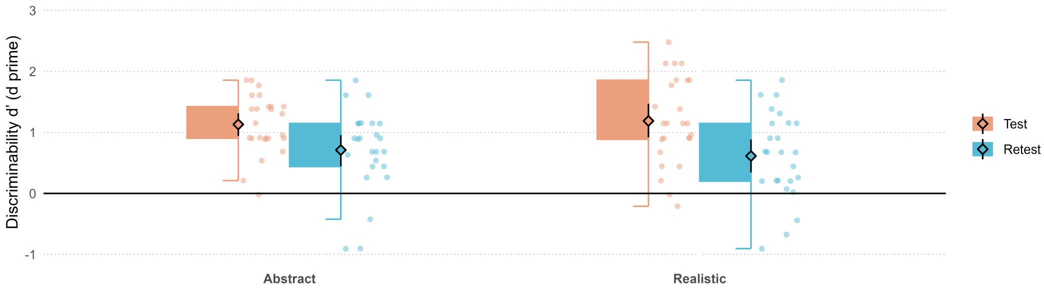

Figure 1 Participants' ability to recognize the landmarks in the environment declines over time but remains above chance, indicating long-term memory retention. *Note: Group means with 95% CIs are plotted beside the boxplots; points indicate individual data and black line chance level.*

24) = 0.902, p = .352). The results show that participants' long-term landmark memory decreases over the test session, regardless of the condition (Figure 2). Participants' retest response bias was significantly higher than zero for the abstract (t(24) = 6.13, p < .001) and the realistic (t(24) = 7.11, p < .001) conditions. Furthermore, the ANOVA results revealed a significant main effect of the test session on response bias (F(1, 24) = 13.29, p = .001), indicating an increase toward "*no*" responses between the test (M = 0.32, SD = 0.34) and retest (M = 0.57, SD = 0.42) sessions. However, there was no main effect of the condition (F(1, 24) = 0.286, p = .597) and no interaction with the test session (F(1, 24) = 1.395, p = .249).

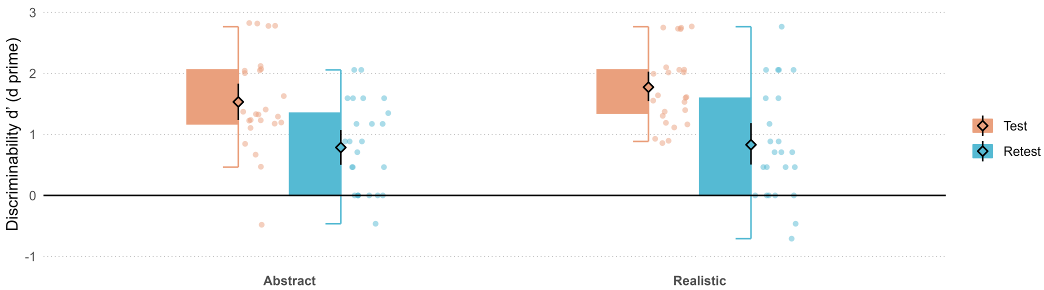

Figure 2 Participants' ability to recognize the landmarks on the mobile map declines over time but remains above chance, indicating long-term memory retention. *Note: Group means with 95% CIs are plotted beside the boxplots; points indicate individual data and black line chance level.*

3.2 Route memory retention

Participants' long-term memory retention of route knowledge was above chance for the abstract (t(24) = 3.23, p = .002) and the realistic (t(24) = 5.37, p < .001) conditions (Figure 3). The ANOVA results did not reveal significant main effects of the test session (F(1, 24) = 0.800, p = .380) and the landmark visualization condition (F(1, 24) = 1.169, p = .290) on route knowledge. The interaction effect between the test session and the condition was also not significant ($F(1, 24) = 0.033$, $p = .857$). These results indicate that route direction accuracy was unaffected between the test and retest session (Figure 3), showing that participants retained long-term route knowledge even after one single route exposure.

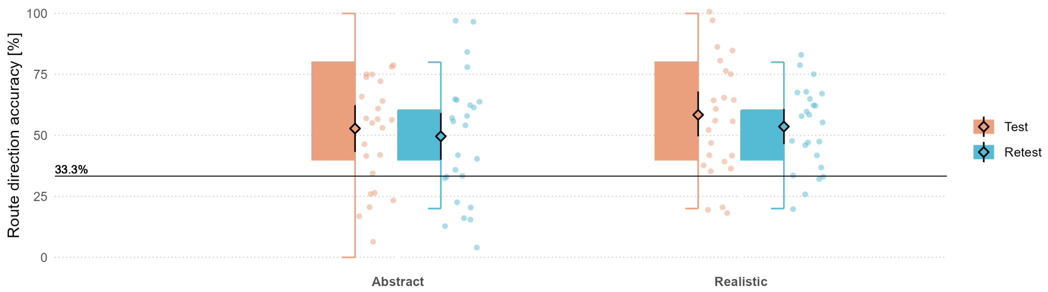

Figure 3 Route knowledge performance remains unchanged over time, and the above-chance performance indicates long-term memory retention. *Note: Group means with 95% CIs are plotted beside the boxplots; points indicate individual data and black line chance level.*

4 Discussion

We conducted a longitudinal study to assess how well participants retain long-term landmark and route memory that was acquired two years ago from one single exposure to a real-world route during a navigation task aided by a mobile map enriched with task-relevant landmark information. Our preliminary results indicate that landmark and route knowledge that was gained from just a single route exposure is retained over a very long time period [33]. The results revealed that regardless of the landmark visualization style, wayfinders' landmark knowledge decreased over the test session, while route knowledge performance was unaffected.

The decrease in landmark memory can be explained by the fact that long-term spatial memory is formed over increased exposure to the environment [24, 33], while the participants in our study were exposed to the real-world route only once. Meanwhile, route knowledge retention between the study sessions could be explained by the fact that when prompted with the images of the task-relevant landmarks, participants could integrate the idiothetic body-motion cues acquired during the active movement in the environment [1] with the presented landmark information and were able to determine their directional heading [5, 31]. That is, being able to associate the specific landmark with a specific action, in this case, the turning direction taken at that landmark [8]. Hence, this might indicate that once the relationship between the visual landmark cue and the idiothetic information is acquired, the integration appears to be long-lasting [1].

We did not find an influence of the abstract 3D and realistic 3D landmark visualization style on wayfinders' long-term landmark and route memory retention. The lack of differences between landmark visualization styles aligns with previous research findings showing that while participants prefer realistic 3D depictions, the long-term retention of environment information derived from a map does not necessarily improve with increased realism [20, 17, 18, 16, 6]. The lack of differences between landmark visualization styles could also be attributed to the lack of significant effects on the spatial learning outcomes in the initial study (see [16]). Another explanation could be the fact that the visual differences between the abstract and realistic 3D landmarks are too subtle and that they both provide the necessary visuospatial information for spatial knowledge formation [1, 26, 4]. Hence, a salient depiction of landmarks as 3D symbols at relevant decision points [30, 32], regardless of the level of detail, could have provided the necessary information to facilitate short-term [1, 16] and long-term spatial memory retention [22, 5].

Limitations and future work

While we present only preliminary results on the long-term retention of landmark and route knowledge acquired two years ago in a map-aided real-world navigation task, some limitations should be pointed out. First, we managed to recruit only 25 out of 46 participants who joined the initial navigation study, and our results might lack statistical power. However, this response rate exceeded our expectations, given that the present study had not initially been planned. Thus, the participants were not asked to agree to return for a follow-up study, and it was expected that some participants would move away after the completion of the initial study, given the student population we had primarily recruited from. Furthermore, while this is not an unusual sample size for longitudinal studies [3, 13], in future work, we plan to employ linear mixed-effect models on participants' per-trial responses to enhance statistical power (see study's preregistration report under supplementary material). Specifically, we plan to investigate whether self-reported spatial abilities [16, 3], GPS reliance and dependency [3], spatial orientation abilities [10], and landmark visualization styles [16] relate to participants' long-term retention of landmark, route, and survey knowledge.

Second, while it was not the intention of this study to investigate the effect of increased environmental exposure on long-term spatial memory, 6 (24%) of our participants reported having been to the navigated route since the initial study took place. Considering the real-world nature of the initial study and the unplanned nature of the follow-up study, we could not control for this. However, since increased exposure might influence long-term spatial memory [24, 33, 13, 2], we plan to control for the effect of environmental exposure in our future planned analyses. Finally, our study investigated participants' long-term landmark and route memory retention acquired in a real-world navigation study with the aid of a mobile map enriched with visually salient landmarks and lacks a no-landmark control condition. While previous navigation studies have provided empirical evidence that the presence of landmarks facilitates spatial learning [27, 9], future work should consider investigating the role of landmark presence on long-term spatial memory formation and retention. Additionally, while our study shows that participants retained some meaningful spatial memory after a two-year period, more work is required to understand the factors behind spatial memory decay over different time periods [25].

5 Conclusions and implications

Taken together, the results of this longitudinal study show that participants retain meaningful long-term landmark and route knowledge that was acquired two years prior from a single exposure to a real-world environment during a navigation task aided by a mobile map enriched with visually salient landmarks. The study highlighted that the retention of spatial information was not affected by the landmark visualization style of the accompanying mobile map. Our study contributes to a severely lacking area of research into long-term spatial memory by showing quite remarkable retention of spatial knowledge derived from a limited encoding period, with no planned requirement for recall after the initial study, and re-tested after a long interval. We hope our findings can motivate future longitudinal work to better understand spatial memory of very long time spans.

References

1. E. R. Chrastil and W. H. Warren. Active and passive contributions to spatial learning. *Psychonomic Bulletin & Review*, 19:1–23, 2012. doi:10.3758/s13423-011-0182-x.
2. L. L. Corazzini, C. Thinus-Blanc, M.-P. Nesa, G. C. Geminiani, and P. Péruch. Differentiated forgetting rates of spatial knowledge in humans in the absence of repeated testing. *Memory*, 16(7):678–688, 2008. doi:10.1080/09658210802286931.
3. L. Dahmani and V. D. Bohbot. Habitual use of GPS negatively impacts spatial memory during self-guided navigation. *Scientific Reports*, 10:6310, 2020. doi:10.1038/s41598-020-62877-0.
4. A. D. Ekstrom. Why vision is important to how we navigate. *Hippocampus*, 25(6):731–735, 2015. doi:10.1002/hipo.22449.
5. R. A. Epstein and L. K. Vass. Neural systems for landmark-based wayfinding in humans. *Philosophical Transactions of the Royal Society B*, 369:20120533, 2014. doi:10.1098/rstb.2012.0533.
6. C. Franke and J. Schweikart. Mental representation of landmarks on maps: Investigating cartographic visualization methods with eye tracking technology. *Spatial Cognition & Computation*, 17(1-2):20–38, 2017. doi:10.1080/13875868.2016.1219912.
7. A. L. Gardony, T. T. Brunyé, and H. A. Taylor. Navigational Aids and Spatial Memory Impairment: The Role of Divided Attention. *Spatial Cognition & Computation*, 15(4):246–284, 2015. doi:10.1080/13875868.2015.1059432.
8. S. Gillner and H. A. Mallot. Navigation and Acquisition of Spatial Knowledge in a Virtual Maze. *Journal of Cognitive Neuroscience*, 10(4):445–463, 1998. doi:10.1162/089892998562861.
9. H. Heft. The role of environmental features in route-learning: Two exploratory studies of way-finding. *Environmental Psychology and Nonverbal Behavior*, 3(3):172–185, 1979. doi:10.1007/BF01142591.
10. M. Hegarty and D. Waller. A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*, 32(2):175–191, 2004. doi:10.1016/j.intell.2003.12.001.
11. C. Hilton, A. Kapaj, and S. I. Fabrikant. Landmark sequence learning from real-world route navigation and the impact of navigation aid visualisation style. *Journal of Cognition*, 6(1):41, 2023. doi:10.5334/joc.307.
12. C. Hilton, A. Kapaj, and S. I. Fabrikant. Fixation-related potentials during mobile map assisted navigation in the real world: The effect of landmark visualization style. *Attention, Perception, & Psychophysics*, 2024. doi:10.3758/s13414-024-02864-z.
13. M. Hirshhorn, C. Grady, R. S. Rosenbaum, G. Winocur, and M. Moscovitch. The hippocampus is involved in mental navigation for a recently learned, but not a highly familiar environment: A longitudinal fMRI study. *Hippocampus*, 22(4):842–852, 2012. doi:10.1002/hipo.20944.
14. T. Ishikawa. Satellite Navigation and Geospatial Awareness: Long-Term Effects of Using Navigation Tools on Wayfinding and Spatial Orientation. *The Professional Geographer*, 71(2):197–209, 2019. doi:10.1080/00330124.2018.1479970.
15. A. Jeneson and L. R. Squire. Working memory, long-term memory, and medial temporal lobe function. *Learning & Memory*, 19(1):15–25, 2012. doi:10.1101/lm.024018.111.
16. A. Kapaj, C. Hilton, S. Lanini-Maggi, and S. I. Fabrikant. The influence of landmark visualization style on task performance, visual attention, and spatial learning in a real-world navigation task. *Spatial Cognition & Computation*, 2024. doi:10.1080/13875868.2024.2328099.
17. A. Kapaj, S. Lanini-Maggi, C. Hilton, B. Cheng, and S. I. Fabrikant. How does the design of landmarks on a mobile map influence wayfinding experts' spatial learning during a real-world navigation task? *Cartography and Geographic Information Science*, 50(2):197–213, 2023. doi:10.1080/15230406.2023.2183525.
18. A. Kapaj, E. Lin, and S. Lanini-Maggi. The Effect of Abstract vs. Realistic 3D Visualization on Landmark and Route Knowledge Acquisition. In T. Ishikawa, S. I. Fabrikant, and S. Winter, editors, *15th International Conference on Spatial Information Theory (COSIT 2022)*, volume 240, pages 15:1–15:8, 2022. doi:10.4230/LIPIcs.COSIT.2022.15.

19 J. W. Kelly and T. P. McNamara. Spatial Memory and Spatial Orientation. In C. Freksa, N. S. Newcombe, P. Gärdenfors, and S. Wölfl, editors, *Spatial Cognition VI. Learning, Reasoning, and Talking about Space*, pages 22–38, 2008. doi:10.1007/978-3-540-87601-4_5.

20 H. Liao, W. Dong, C. Peng, and H. Liu. Exploring differences of visual attention in pedestrian navigation when using 2D maps and 3D geo-browsers. *Cartography and Geographic Information Science*, 44(6):474–490, 2017. doi:10.1080/15230406.2016.1174886.

21 D. Makowski. The psycho Package: an Efficient and Publishing-Oriented Workflow for Psychological Science. *Journal of Open Source Software*, 3(22):470, 2018. doi:10.21105/joss.00470.

22 A. M. P. Miller, L. C. Vedder, L. M. Law, and D. M. Smith. Cues, context, and long-term memory: the role of the retrosplenial cortex in spatial cognition. *Frontiers in Human Neuroscience*, 8, 2014. doi:10.3389/fnhum.2014.00586.

23 S. Münzer and C. Hölscher. Entwicklung und Validierung eines Fragebogens zu räumlichen Strategien. *Diagnostica*, 57(3):111–125, 2011. doi:10.1026/0012-1924/a000040.

24 E. Z. Patai, A.-H. Javadi, J. D. Ozubko, A. O'Callaghan, S. Ji, J. Robin, C. Grady, G. Winocur, R. S. Rosenbaum, M. Moscovitch, and H. J. Spiers. Hippocampal and Retrosplenial Goal Distance Coding After Long-term Consolidation of a Real-World Environment. *Cerebral Cortex*, 29(6):2748–2758, 2019. doi:10.1093/cercor/bhz044.

25 G. A. Radvansky, A. C. Doolen, K. A. Pettijohn, and M. Ritchey. A new look at memory retention and forgetting. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 48(11):1698–1723, 2022. doi:10.1037/xlm0001110.

26 S. Ramanoël, M. Durteste, A. Bizeul, A. Ozier-Lafontaine, M. Bécu, J.-A. Sahel, C. Habas, and A. Arleo. Selective neural coding of object, feature, and geometry spatial cues in humans. *Human Brain Mapping*, 43(17):5281–5295, 2022. doi:10.1002/hbm.26002.

27 G. Sharma, Y. Kaushal, S. Chandra, V. Singh, A. P. Mittal, and V. Dutt. Influence of Landmarks on Wayfinding and Brain Connectivity in Immersive Virtual Reality Environment. *Frontiers in Psychology*, 8, 2017. doi:10.3389/fpsyg.2017.01220.

28 H. J. Spiers and E. A. Maguire. The neuroscience of remote spatial memory: A tale of two cities. *Neuroscience*, 149(1):7–27, 2007. doi:10.1016/j.neuroscience.2007.06.056.

29 H. Stanislaw and N. Todorov. Calculation of signal detection theory measures. *Behavior Research Methods, Instruments, & Computers*, 31:137–149, 1999. doi:10.3758/BF03207704.

30 B. J. Stankiewicz and A. A. Kalia. Acquistion of structural versus object landmark knowledge. *Journal of Experimental Psychology: Human Perception and Performance*, 33(2):378–390, 2007. doi:10.1037/0096-1523.33.2.378.

31 J. S. Taube. The Head Direction Signal: Origins and Sensory-Motor Integration. *Annual Review of Neuroscience*, 30:181–207, 2007. doi:10.1146/annurev.neuro.29.051605.112854.

32 T. Thrash, S. Lanini-Maggi, S. I. Fabrikant, S. Bertel, A. Brügger, S. Credé, C. T. Do, G. Gartner, H. Huang, S. Münzer, and K.-F. Richter. The Future of Geographic Information Displays from GIScience, Cartographic, and Cognitive Science Perspectives. In S. Timpf, C. Schlieder, M. Kattenbeck, B. Ludwig, and K. Stewart, editors, *14th International Conference on Spatial Information Theory (COSIT 2019)*, volume 142, pages 19:1–19:11, 2019. doi:10.4230/LIPIcs.COSIT.2019.19.

33 G. Winocur, M. Moscovitch, and B. Bontempi. Memory formation and long-term retention in humans and animals: Convergence towards a transformation account of hippocampal–neocortical interactions. *Neuropsychologia*, 48(8):2339–2356, 2010. doi:10.1016/j.neuropsychologia.2010.04.016.