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The development of landmark, route, and survey knowledge through repeated mobile map-assisted navigation episodes

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Abstract. The process by which navigators develop a cognitive map of an unfamiliar environment with increasing exposure has been extensively studied. How this process unfolds during mobile map-assisted navigation remains an open research question. We thus conducted an outdoor pedestrian navigation study (N = 45) in a residential neighborhood initially unknown to participants. Participants were asked to navigate a predefined route using a mobile map three times across three separate days within a week. Following each navigation session, participants were tested on their evolving spatial knowledge of the traversed environment. We find that participants acquired meaningful landmark, route, and survey knowledge on their first environmental exposure and that all three types of spatial knowledge increased in later sessions. We also discovered that landmark direction information developed faster than distance information in participants' cognitive maps. These highly ecologically valid results contribute to a better understanding of the role of increased environmental exposure on the continuous and parallel development of spatial knowledge during map-assisted navigation.

Submission Type. Theory

BoK Concepts. Usability of maps, Satellite Navigation systems

Keywords. spatial learning, real-world navigation study, mobile map

1 Introduction

Siegel and White (1975) found that already children are able to remember a large environment by repeatedly walking through it. They described this process as integrating the perceived information to develop an accurate mental representation of the environment. This representation contains observed and remembered objects, such as distinct landmarks, connecting routes, and neighborhoods. These objects are hierarchically organized, progressing from an egocentric perspective focused on landmarks and routes to allocentric, map-like mental constructs of the environment (Hirtle and Jonides, 1985). Siegel and White (1975) thus categorized spatial knowledge into landmark, route, and survey knowledge. A widely debated research question concerns how different hierarchies of spatial knowledge evolve with increased environmental exposure. Behavioral studies have shown that three types of spatial knowledge develop in parallel during navigation tasks (Ishikawa and Montello, 2006; Kim and Bock, 2021). Neuroscientific evidence further suggests that navigators process and represent landmarks, the distance and direction between them, and the boundary information of space in distinct brain structures, with a clear distribution of tasks among specialized cells (Epstein and Vass, 2014; Parra-Barrero et al., 2023).

Over the last decades, there has been growing interest in understanding how advancements in navigation tools influence spatial knowledge acquisition (McKinlay, 2016). These tools are equipped with Global Navigation Satellite System (GNSS) infrastructure (e.g., Global Positioning System, GPS) and display the geographic information on a mobile map interface. Learning spatial layouts from maps has been shown to facilitate the acquisition of allocentric spatial knowledge, such as the relative locations and Euclidean distances between landmarks (Richardson et al., 1999; Thorndyke and Hayes-Roth, 1982; Zhang et al., 2014). However, the increased reliance on turn-by-turn GNSS-equipped mobile map applications appears to negatively impact spatial memory during navigation tasks (Gardony et al., 2015; Ben-Elia, 2021), leading to long-term deterioration in navigation ability (Ruginski et al., 2019; Topete et al., 2024; Ying et al., 2024). Despite extensive research on the behavior and neural mechanisms underlying non-map-assisted navigation, studies investigating how navigators learn their surroundings and develop different hierarchies of spatial knowledge during map-assisted navigation tasks are scarce. To our best knowledge, only one study has investigated the acquisition of landmark and survey knowledge in map-assisted navigation tasks within a Virtual Reality (VR) environment (Zhao et al., 2023). This study found a consistent increase in both landmark and survey knowledge across four exposures to the environment, while route knowledge was not investigated.

We conducted a real-world navigation study to investigate how wayfinders develop landmark, route, and survey knowledge of the traversed environment during repeated navigation tasks assisted with a mobile map. We hypothesized that participants would acquire all three types of spatial knowledge with limited exposure (H1) and that spatial knowledge would develop in parallel with increased environmental exposure (H2).

2 Methods

2.1 Participants

A total of 46 healthy adults participated in the experiment. Data from one participant were excluded because they did not understand the tasks correctly. The final dataset included 45 participants (25 females, average age = 27 years, range = 20 – 35 years) whose data were analyzed and are discussed in this paper. All participants had normal or corrected-to-normal vision and no history of psychiatric disorders. The study received ethical approval from the Ethics Committee of the University of Zurich (no. 23.12.23), and all participants provided written informed consent before the start of the experiment.

2.2 Experimental Design

The experiment was conducted outdoors in a residential neighborhood in Zurich, Switzerland, which was initially unknown to the participants. We followed a 3x2 within-subject design. Participants navigated the routes repeatedly three times on three separate days within a week (independent variable: navigation session with three levels). In each session, they performed route-following tasks on two distinct routes (Route A and Route B). On one of the two routes, participants used a mobile map to assist in their navigation. On the other route, they followed the lead of an experimenter without access to any map, which is not the focus of this paper. Participants' acquired spatial knowledge was assessed in a subsequent test phase. The dependent variables (DVs) included participants' performance in the spatial knowledge tests, which are detailed in the following sections.

2.3 Materials

As depicted in Figure 1A, the two chosen routes share the same starting point and have similar lengths. Route A is approximately 750 meters long, and Route B is approximately 680 meters long. Both routes contain 10 intersections, with three left turns, four right turns, and three straight movements. The assignment of the two navigation conditions to the routes was counterbalanced across participants. The mobile map used in this experiment (Figure 1B) was adapted from OpenStreetMap and was presented to participants on a Samsung Galaxy tablet with a 1920 x 1200 pixels resolution. This map displayed the predefined route to be followed, along with the starting point, destination, and the participant's current location. Participants could freely interact with the map (e.g., zoom, pan, and rotate).

The test phase consisted of four tasks targeting different categories of spatial knowledge. Specifically, we utilized a landmark recognition task to assess landmark knowledge (Wunderlich and Gramann, 2021), an action recall task to evaluate route knowledge (Burte and Montello, 2017), and a within-route direction task (Burte and Montello, 2017) and a distance estimation task (Kapaj et al., 2024) to assess survey knowledge. We selected 32 buildings from each route to serve as task-relevant landmarks, ensuring they were not visible from the starting point, and used them in the spatial knowledge test. The landmarks were randomly divided into four groups of eight. During each experimental session, two groups of landmarks were utilized for the spatial knowledge tasks. One group, designated as the repeated landmark group, appeared in all tests across all three sessions, while the remaining three groups were each assigned to a different session. The assignment of the repeated landmark group and the other three landmark groups to three experimental sessions were counterbalanced across participants.

For the landmark recognition task, participants were presented with images of 16 task-relevant landmarks, taken from the same perspective as viewed while traversing the route, and eight novel landmarks that were not encountered along the route, for a total of 24 trials. They were asked to indicate whether they recognized having seen them while traversing the route or not. In the action recall task, participants viewed the same 16 task-relevant landmarks and were asked to specify which of the three possible actions they recalled taking upon encountering each landmark on their way to the destination (i.e., going straight, turning left, or turning right). For the within-route direction estimation task, participants faced 112° east from true north at the starting point and drew an arrow in a circle to indicate the direction of each task-relevant landmark. For the distance estimation task, participants estimated the straight-line distance in meters from the starting point to each task-relevant landmark. A reference distance of 40 meters, corresponding to the distance from the starting

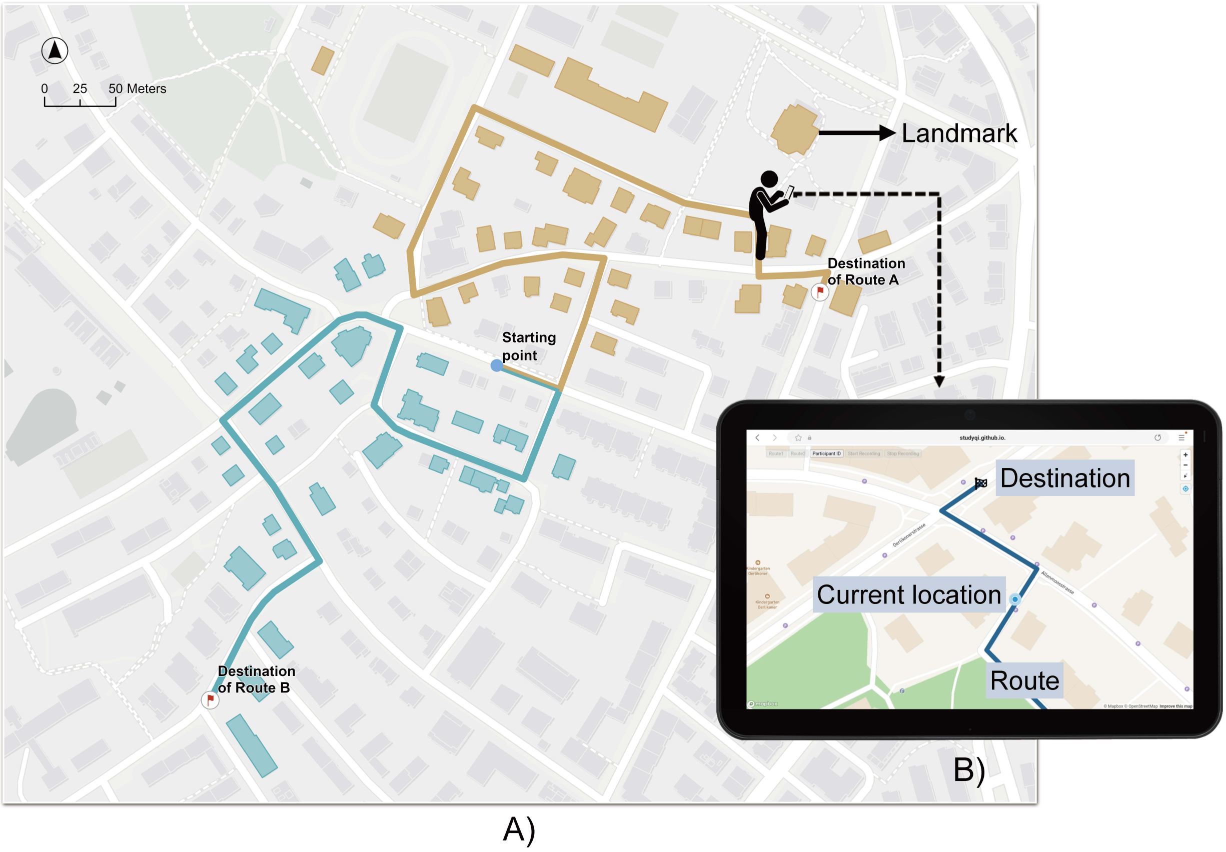

Figure 1. (A) The map depicting the experimental area and the two chosen routes. The highlighted buildings show the selected task-relevant landmarks that were used in the spatial knowledge test. (B) The mobile map that participants used to assist their navigation.

point to the nearest intersection, was shown for training purposes.

2.4 Procedure

On each experimental day, the experimenters led participants to the starting point of the routes. Before the navigation phase, they were informed that their knowledge about the buildings encountered while navigating the route would be tested later. Upon reaching the destination, participants were instructed to navigate the route in reverse without any assistance. If participants took a wrong turn at an intersection, the experimenter shadowing them called them back to the intersection to make a new decision. After returning to the starting point, participants completed the spatial knowledge tests before starting the navigation phase for the second route. Each experiment session lasted approximately two hours, and participants were compensated with 60 CHF for completing all three sessions. The experiment was conducted between June and November 2024.

2.5 Data Analysis

To assess landmark knowledge, we calculated the discriminability index *d prime* (DV 1) calculated as [*d'* = *z(hit rate)* – *z(false alarm rate)*] based on signal detection theory (SDT; Tanner and Swets, 1954) using the *psycho* package (Makowski, 2018) in R (v. 4.4.2). The discriminability index measures participants' ability to distinguish task-relevant landmarks from novel landmarks, and a value of zero indicates chance performance. We used action recall accuracy (DV 2) to assess participants' route knowledge, calculated as a percentage of correctly answered trials relative to the total number of trials, where a value of 33.33% indicates chance performance. For direction and distance estimation tasks, absolute errors (DV 3 and DV 4) were computed as the difference between participants' estimates and the actual direction or distance from the starting point to the landmarks, respectively. An angular error of 90 degrees in the direction estimation task indicates chance-level performance.

We ran one-sample t-tests on DV 1, DV 2, and DV 3 in the first session to compare participants' task performance with chance-level performance. Furthermore, we ran repeated-measures ANOVAs on all the DVs using the *ez* package (Lawrence, 2016) in R. The session was used as the factor to investigate whether participants' acquired spatial knowledge differs between the study sessions. Mauchly's Test of Sphericity was performed for all DVs, and for those where sphericity was violated, Greenhouse-Geisser correction was applied. Post-hoc paired t-tests were utilized to compare the differences in participants' performance between each pair of sessions. We applied a Bonferroni correction to adjust the p-values for multiple comparisons.

Data Availability

The data used in this paper and the analyses script are available at the following link: https://doi.org/10.17605/OSF.IO/9KGXN

3 Results

The one-sample t-test revealed that participants' spatial knowledge acquisition performance in the first session was significantly better than chance (Figure 2A, Figure 2B, and Figure 2C) for landmark knowledge ($M_{session1}$ = 0.69, $SD_{session1}$ = 0.54; $t(44)$ = 8.53, p < .001), route knowledge ($M_{session1}$ = 53.75, $SD_{session1}$ = 16.45; $t(44)$ = 8.33, p < .001), and direction estimation as a measure of survey knowledge ($M_{session1}$ = 51.19, $SD_{session1}$ = 18.02, $t(44)$ = -14.45, p < .001).

The repeated-measures ANOVA analyses revealed significant differences across the three sessions (Figure 2) in landmark recognition ($F(2, 72.16)$ = 30.87, p < .001), action recall accuracy ($F(2, 88)$ = 14.04, p < .001), direction estimation error ($F(2, 88)$ = 25.49, p < .001), and distance estimation error ($F(2, 67.76)$ = 8.87, p = .001). Post-hoc paired t-tests revealed that, as shown in Figure 2A, participants' performance in recognizing the seen task-relevant landmarks improved significantly from the first to the second session ($M_{session2}$ = 1.17, $SD_{session2}$ = 0.69; $t(44)$ = -5.34, p < .001) and improved further from the second to the third session ($M_{session3}$ = 1.62, $SD_{session3}$ = 0.94; $t(44)$ = -3.72, p = .002). The difference between the first and the third session was also significant ($t(44)$ = -6.70, p < .001). Participants action recall accuracy differed significantly between the first and the second session ($M_{session2}$ = 61.67, $SD_{session2}$ = 20.15; $t(44)$ = -3.25, p = .007) and between the first and the third session ($M_{session3}$ = 66.67, $SD_{session3}$ = 21.57; $t(44)$ = -4.81, p < .001), but not between the second and the third session ($t(44)$ = -2.24, p = .091).

In terms of direction estimation (Figure 2C), we find that participants' performance improved significantly from the first to the second session ($M_{session2}$ = 41.9, $SD_{session2}$ = 15.81; $t(44)$ = 3.82, p = .001), and from the first to the third session ($M_{session3}$ = 38.81, $SD_{session3}$ = 14.68; $t(44)$ = 4.68, p < .001). However, the difference between the second and the third session was not significant ($t(44)$ = 1.62, p = .336). Participants' performance in distance estimation (Figure 2D) showed no significant difference between the first ($M_{session1}$ = 125.6, $SD_{session1}$ = 65.80) and the second session ($M_{session2}$ = 110.9, $SD_{session2}$ = 66.72; $t(44)$ = 1.68, p = .299), but improved significantly from the second to the third session ($M_{session3}$ = 91.7, $SD_{session3}$ = 62; $t(44)$ = 3.35, p = .005). The difference between the first and the third session was also significant ($t(44)$ = 3.56, p = .003).

4 Discussion

We conducted a map-assisted navigation study to investigate wayfinders' development of landmark, route, and survey knowledge over three exposures to a real-world environment. Consistent with our first hypothesis (H1), we found that participants' landmark, route, and survey knowledge (i.e., participants' performance in landmark direction estimation) of the traversed environment was significantly better than chance already after the first exposure. This finding aligns with earlier studies on non-map-assisted navigation, which demonstrated that navigators acquire metric knowledge of unfamiliar environments immediately after experiencing them and not after having acquired landmark and route knowledge (Ishikawa and Montello, 2006; Montello, 1998; Hirtle and Hudson, 1991).

In line with our second hypothesis (H2), we found that participants' landmark, route, and direction knowledge improved concurrently from the first session to the second session. These findings are consistent with the results of Kim and Bock (2021), who reported that spatial knowledge acquired after an unaided VR wayfinding task increased and developed in parallel over the study sessions. Furthermore, our landmark knowledge findings replicate those of Zhao et al. (2023), who reported improved landmark knowledge with repeated free exploration of an urban VR environment aided by a map. Our study extends this finding to real-world route-following tasks, with longer intervals between navigation sessions. The lack of significant improvements in route direction recall and direction estimation from the second to the third session may be attributed to the possibility that participants already reached ceiling performance (Huffman and Ekstrom, 2019).

Although the results indicated a continuous development in survey knowledge over sessions, we observed that participants' direction knowledge improved primarily in the first two sessions, while distance knowledge developed in the third session. It should be noted that, due to the lack of a chance level for the distance estimation task, we cannot determine how much participants learned about distance in the first session. Nonetheless, the results from the first session were comparable to those of Kapaj et al. (2024), who investigated spatial learning in an outdoor map-assisted navigation task. In their study, participants' performance in distance estimation was very low compared to the direction estimation after one single route exposure. Our findings suggest that acquiring distance knowledge with limited exposure is more challenging than acquiring direction knowledge for mobile map-assisted navigators. However, in the

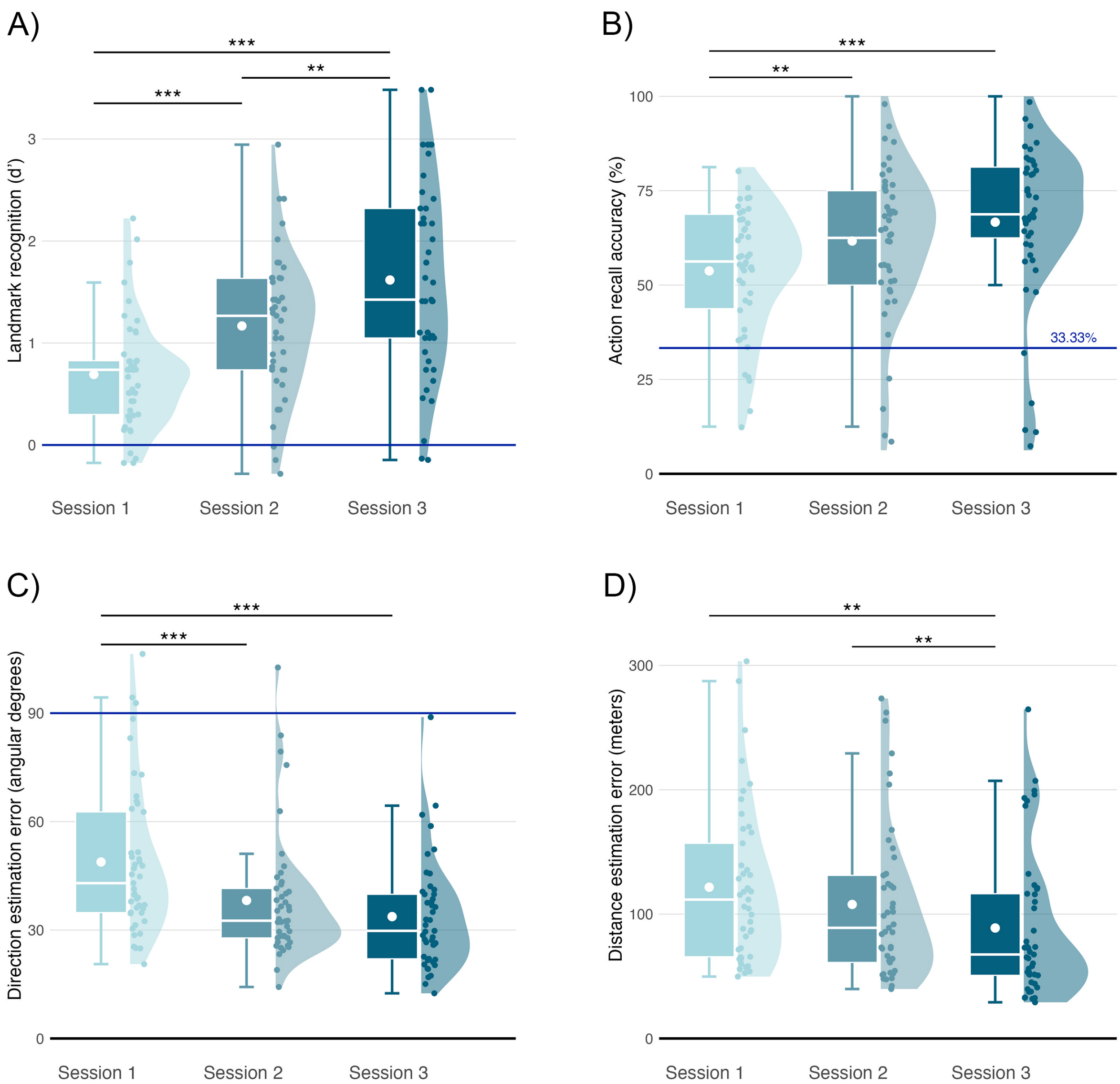

Figure 2. Participants' performance in spatial knowledge test by sessions and the statistical results of the pairwise t-tests. The white line indicates the median, the white dot indicates the mean, and the whiskers indicate the 95% confidence interval. The blue line represents the chance level performance. * indicates $p < .05$, ** indicates $p < .01$, *** indicates $p < .001$.

non-map-assisted route-following study conducted by Ishikawa and Montello (2006), the asynchrony in the development of direction and distance knowledge over sessions was not observed. The discrepancy between our results and the results of Ishikawa and Montello (2006) could be due to the presence of a mobile map in our study, which might have facilitated direction awareness in the earlier sessions and distance awareness in the later sessions. Yet, our data do not tell us whether the mobile map helped participants form a more accurate internal representation of the environment, whether they directly used the map's information about the environment's layout to complete the task, or whether both approaches worked in an integrated manner. Previous studies comparing spatial knowledge acquisition through reading a map and directly experiencing the environment have shown that map learning facilitates allocentric direction estimation while leading to poorer performance in egocentric direction estimation (Richardson et al., 1999; Thorndyke and Hayes-Roth, 1982; Zhang et al., 2014). We thus believe our findings on direction knowledge are better explained by the first inference that participants did integrate information from the map with their own cognitive representation of the environment. If they had learned the environment only from the map, it would have resulted in worse direction estimation performance captured with the egocentric pointing task. Prior research suggests that individual spatial abilities also play a role in determining whether navigators benefit from maps in spatial learning (Stites et al., 2020). Future analyses will examine participants' development of spatial knowledge across the study session and the experimental conditions (i.e., map vs. non-map) while accounting for their spatial abilities.

5 Conclusion

Taken together, the findings from this outdoor mobile map-assisted navigation study show that participants were able to acquire landmark, route, and survey knowledge (i.e., direction knowledge) on their first exposure to the environment. Taken further, participants concurrently acquired landmark, route, and survey knowledge (i.e., direction knowledge) over the first two sessions, and they continuously acquired landmark and survey knowledge (i.e., distance knowledge) in the third session. Our study offers valuable insights into how increased environmental exposure contributes to the parallel acquisition of spatial knowledge during map-assisted navigation tasks. Future work should examine our findings with more experimental sessions and investigate the development of spatial knowledge in later stages. It would also be interesting to investigate how different levels of automation (e.g., with or without self-localization options; Brügger et al., 2019) and various methods of presenting spatial information in navigation aids influence the findings reported in this paper.

Declaration of Generative AI in writing

The authors declare that they have not used Generative AI tools in the preparation of this manuscript. All intellectual and creative work, including the analysis and interpretation of data, is original and has been conducted by the authors without AI assistance.

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