Habitual Use of Navigation Systems Impairs Spatial Learning Depending on Navigation Strategy

Qi Ying[1]
Department of Geography, University of Zurich, Switzerland

Christopher Hilton
Institute of Psychology and Ergonomics, Technische Universität Berlin, Germany

Sara I. Fabrikant
Department of Geography, University of Zurich, Switzerland

Abstract

Previous research is inconsistent on how the habitual use of navigation systems affects spatial learning of pedestrian navigators. The present study investigates whether individual differences in navigation strategy choices moderate this. Participants (N = 45) completed questionnaires assessing their navigation strategies and their reliance on pedestrian navigation systems. Spatial learning was evaluated through a real-world navigation experiment conducted in an initially unfamiliar urban environment. Participants repeatedly navigated two routes across three separate days either assisted by a mobile map or by following an experimenter. Different types of spatial knowledge were assessed using five tasks. Linear mixed-effects (LME) models were employed to analyze the relationships between measures. We found that greater habitual use of navigation systems was associated with worse route knowledge acquisition, but only for participants who relied on a map-based navigation strategy. Greater habitual use of navigation systems was also linked to worse survey knowledge acquisition, but only for mobile map-assisted navigators. This new empirical evidence contributes to a more nuanced understanding of how habitual use of navigation systems may impair spatial learning of pedestrian navigators, highlighting the moderating role of individual navigation strategies and navigation conditions.

2012 ACM Subject Classification Applied computing → Psychology; Human-centered computing → Empirical studies in HCI; Applied computing → Cartography

Keywords and phrases digital navigation aids, mobile maps, wayfinding, navigation strategy, spatial knowledge

Digital Object Identifier 10.4230/LIPIcs.COSIT.2026.22

Category Short Paper

Supplementary Material *Dataset*: `https://doi.org/10.17605/OSF.IO/E6UKX`

Funding This work was supported by the Swiss National Science Foundation [grant number 10003761] and the China Scholarship Council [grant number 202206040035].

1 Introduction

The rapid development and ubiquitous use of navigation technology have sparked debates on how habitual uses of these technologies may weaken users' innate navigation abilities over the long term. Global Navigation Satellite System technology (GNSS) has revolutionized everyday navigation by taking over cognitively demanding navigation tasks from the assisted navigator. Current location is automatically displayed on the mobile map, while turn-by-turn directions are provided with the navigation system. This reduces the need of the navigator to attend to allocentric relationships of features in the traversed environment. While navigation

[1] Geographic Information Visualization & Analysis (GIVA), University of Zurich – Irchel, Winterthurstrasse 190, 8057 Zurich, Switzerland

systems greatly enhance wayfinding effectiveness, studies have suggested that reliance on these systems may come at the cost of a deeper understanding of and interactions with the traversed environment, and thus limits spatial learning [1].

Long-term use of navigation systems could result in a decline of the users' innate spatial ability. Dahmani and Bohbot reported that greater habitual use of navigation systems during a three-year period was associated with a larger decline in spatial memory assessed in a VR maze [3]. In another VR-based study, it was found that habitual use of such systems had a negative effect on spatial learning even after controlling for the tendency of navigators with lower navigation ability to rely more heavily on navigation systems [10]. Habitual use of in-car navigation systems by expert taxi drivers impaired their spatial learning, leading to increased cognitive load during navigation [13]. In a resting-state functional magnetic resonance imaging (rs-fMRI) experiment, Fajnerová et al. found that after three months of habitual navigation system use, participants showed reduced functional connectivity between the hippocampus and other brain regions involved in navigation [4], indicating that habitual use of navigation systems is linked to brain health. In contrast, in an online study involving 822 participants, Yavuz et al. found that participants' performance in a video game requiring them to memorize a map and navigate to specified locations was not associated with their habitual use of navigation systems [12]. This finding warrants particular attention, given the very large sample size of the study and a different map-use setting.

Inconsistency in previous findings suggests that other types of individual differences may exist to explain the relationship between navigation system reliance and spatial learning such as, preferred navigation strategy. Individuals who prefer a map-based strategy during navigation tend to rely on mental representations of the environment using an allocentric reference frame to orient themselves, identify destinations, and compute routes. In contrast, individuals who prefer a scene-based strategy rely primarily on their egocentric perception and the sequential memory of landmarks and actions to reproduce previously traveled routes, which more closely aligns with the spatial information communicated by the navigation system [6]. Accordingly, individuals with different navigation strategies may be differentially affected by the habitual use of such systems. This possibility has not been well demonstrated in previous research. Moreover, most of the previous studies examined spatial learning using only a single navigation-assistance type. An exception is Ishikawa's study, which found that habitual use of in-car navigation systems deteriorated spatial learning in both mobile map-assisted and paper map-assisted navigation conditions [7].

In the present study, we investigated how habitual use of GNSS-enabled navigation systems relates to individuals' spatial learning evaluated in map-guided and experimenter-guided navigation. We specifically examined whether this relationship is moderated by individuals' navigation strategy preference. We hypothesized that greater habitual use of navigation systems is negatively associated with spatial learning of individuals who prefer a map-based navigation strategy. This is because their preferred spatial learning mechanisms may be less frequently engaged and thus less well developed during daily use of turn-by-turn navigation systems (H1). We also expected this detrimental effect to be evident across both navigation conditions (H2).

2 Methods

2.1 Participants

Forty-six participants completed the experiment. One participant was excluded from the analyses due to a misunderstanding of the task instructions. The analyzed sample consisted of 45 participants (25 females, 20 males; mean age = 27 years, SD = 3.45). The study was registered with the ethics committee of the first author's affiliated university (No. 23.12.23). All participants provided written informed consent prior to the experiment and received 60 in the local currency as compensation for their participation in the experiment.

2.2 Experimental design

The experiment followed a within-subjects design and was conducted in a real-world urban environment initially unfamiliar to participants. Each participant navigated two routes (i.e., Route A and Route B, depicted in Figure 1); one route assisted by a mobile map (map-guided condition) and the other by following an experimenter (experimenter-guided condition). The assignment of navigation conditions to routes was counterbalanced across participants; that is, half of the participants navigated Route A with the mobile map, whereas the other half navigated it by following the experimenter. Participants navigated each route in the same manner three times (i.e., three navigation sessions) on three different days within a single week, thus allowing sufficient time for spatial knowledge development. On average, participants completed the second session 44.47 hours after the first session and the third session 119.76 hours after the first session. After navigating each route, participants' spatial learning was tested with five spatial knowledge tasks.

- **Route reversal task.** Participants were asked to reverse the route from each destination back to the starting point without any navigation assistance. If a participant took a wrong turn, the experimenter called them back to the decision point so they could make a new wayfinding choice. The time taken to complete this task was recorded in seconds, reflecting participants' ability to flexibly use different types of spatial knowledge for this wayfinding task.

Once participants reached the starting point again, they were oriented facing 112° East of true North, as depicted in Figure 1, and asked to complete the remaining four tasks.

- **Landmark recognition task.** Participants were presented with photographs of 16 visible landmarks located along the route and visible during navigation, along with eight foils. They indicated whether they had seen each presented landmark during navigation.
- **Route direction task.** The same 16 landmarks were presented again to participants, and they were asked to indicate which of three possible directions they had taken after encountering each landmark (i.e., straight, left, or right turn).
- **Pointing task and distance estimation task.** Participants indicated the direction of each landmark from their current position by drawing an arrow from the center of a circle. Their current location and facing direction were depicted on the circle. They were also asked to estimate the straight-line distance to each landmark in meters. A known distance to the nearest intersection (40 m) was provided as a reference for these distance estimates.

Using the Navigation Strategy Questionnaire [2], we found that 23 participants preferred a scene-based navigation strategy while 22 preferred a map-based navigation strategy. Participants' habitual use of pedestrian navigation systems was assessed using a self-developed background questionnaire with the question "*How often do you use pedestrian navigation systems?*" Participants selected one of the following response options: "*less than once a week,*" "*1–2 times a week,*" "*3–4 times a week,*" "*5–6 times a week,*" or "*7 times or more per week.*" Responses were coded on a scale from 1 (low frequency) to 5 (high frequency) for subsequent analyses.

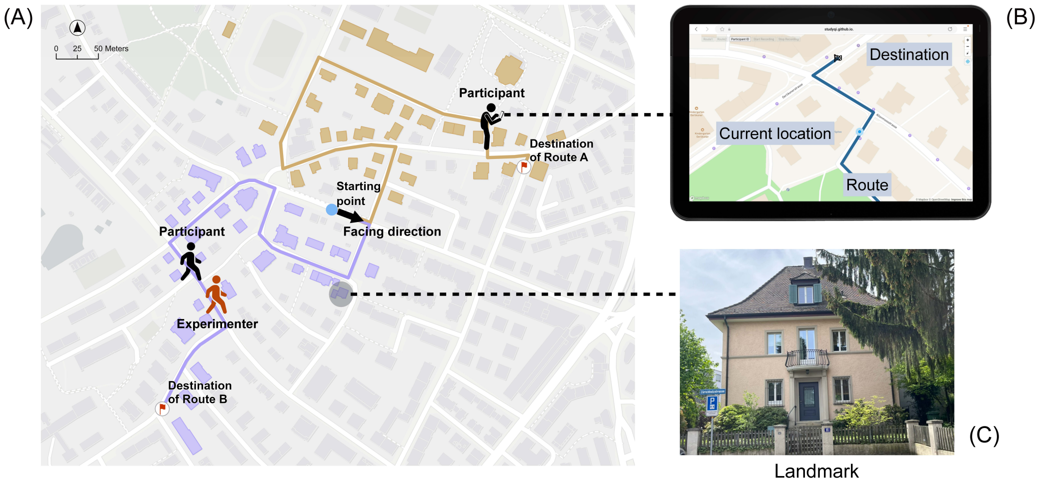

Figure 1 (A) The two navigated routes shared the same starting point and were similar in length (Route A: approximately 750 m; Route B: approximately 680 m) and comparable in structure, with 10 intersections and seven turns. (B) The mobile map contained a base map, the start and destination locations, the route to be followed and the navigator's current location. The labels are only included for explanation in this Figure and were not shown on the mobile map during the experiment. (C) A sample landmark photo used for the spatial knowledge test.

2.3 Procedure

Participants were welcomed to a university laboratory located near the experimental area, where they first gave informed consent and then completed various questionnaires. After the setup of the EEG and the eye tracker, participants were escorted to the starting point near the university and given instructions for the outdoor portion of the experiment. They then performed the route-following, route-reversal, and spatial knowledge tasks for the first route. The same procedure was repeated for the second route they navigated.

2.4 Data analysis

Participants' performance on the landmark recognition task, reflecting their ability to acquire landmark knowledge, was assessed using the discriminability index d prime (d' = z[hit rate] - z[false alarm rate]) based on signal detection theory [11]. Route direction recall accuracy (binary: correct or incorrect) reflected participants' ability to acquire route knowledge. Pointing and distance estimation performance were evaluated using absolute pointing error (in degrees) and the absolute distance estimation error (in meters), respectively. These two indices reflect participants' ability to acquire survey knowledge.

Outlier correction was conducted for each task. For each navigation condition and session combination, participants with extremely poor performance were identified as outliers using a $3 \times$ standard deviation (SD) criterion and were removed from the analyses. In total, six outliers were identified for the pointing task, three for the distance estimation task, and two for the route reversal task. We fitted linear and generalized linear mixed effect (LME and GLME) models to predict spatial knowledge test performance. The models included the following fixed effects: navigation condition (using sum contrasts), session (using successive differences contrasts), navigation strategy (using sum contrasts), and the frequency of navigation system use (continuous). All models incorporated two-way interaction terms for each pair of predictors and included participant ID as a random factor with random intercepts. All analyses were conducted in R (v. 4.4.2).

3 Results

We found a significant main effect of frequency of navigation system use on pointing error. Higher frequency of navigation system use was associated with increased pointing error (β = 2.81, SE = 1.28, t = 2.20, p = .034). No significant main effects of navigation system use were observed for the other tasks in the spatial knowledge test (all $p > .05$).

Regarding the moderating effect of navigation strategy, the LME model for the route direction task revealed a significant interaction between frequency of navigation system use and preferred navigation strategy (β = 0.18, SE = 0.07, t = 2.73, p = .006). Post-hoc analyses indicated that frequency of navigation system use significantly predicted route direction recall accuracy for participants who preferred a map-based navigation strategy (β = -0.19, SE = 0.09, z = -2.12, p = .034), but not for participants who preferred a scene-based navigation strategy (β = 0.17, SE = 0.10, z = 1.77, p = .078). The contrast between these two strategy slopes was also significant (β = 0.36, SE = 0.13, z = 2.73, p = .006). Visual inspection of Figure 2A confirmed that greater habitual use of navigation systems was associated with poorer route direction recall performance, but only for map-based navigators.

Significant interactions between the frequency of navigation system use and navigation condition emerged in the LME models for the pointing task (β = 0.69, SE = 0.33, t = 2.05, p = .041) and the route reversal task (β = -3.33, SE = 1.48, t = -2.26, p = .025). As observed in Figure 2B and examined in post-hoc analyses, higher frequency of navigation system use was associated with increased pointing error in the map-guided condition (β = 3.50, SE = 1.32, z = 2.65, p = .008), but not in the experimenter-guided condition (β = 2.13, SE = 1.32, z = 1.61, p = .108). The contrast between these two condition slopes was significant (β = 1.37, SE = 0.67, z = 2.05, p = .041). For the route reversal task (Figure 2C), a different pattern was observed: the negative association between the frequency of navigation system use with route reversal performance appeared more prominent for the experimenter-guided condition. Despite a significant difference between the condition slopes (β = -6.66, SE = 2.95, t = -2.26, p = .025), the frequency of navigation system use did not significantly predict route reversal performance in either navigation condition, as examined with post-hoc analyses (all ps > .05).

4 Discussion

This study set out to investigate the inconclusive impact of habitual navigation system use on spatial learning in varying navigation assistance conditions, by examining whether this relationship might differ across wayfinders' preferred navigation strategies. We found that the habitual use of navigation systems impaired route knowledge acquisition for participants who preferred an allocentric, map-based navigation strategy, but not other forms of spatial knowledge, partially supporting Hypothesis 1. Our findings also indicated that increased habitual use of navigation systems was associated with greater pointing error, reflecting poorer survey knowledge acquisition, consistent with those reported by Ruginski et al. [10]. Contrary to our prediction that the deteriorating effect would be universal (Hypothesis 2), it was only significant in the map-guided condition.

Taken together, these findings could mean that navigation systems predominantly provide and emphasize egocentric information (e.g., turn-by-turn instructions at intersections), which is relatively easy to process as it requires less cognitively demanding cognitive mechanisms [9]. Consequently, users of such systems may be less spontaneously engaged in processing allocentric map information and thus in forming cognitive maps, which require higher-level learning mechanisms [8]. Somewhat paradoxically, greater reliance on navigation systems may

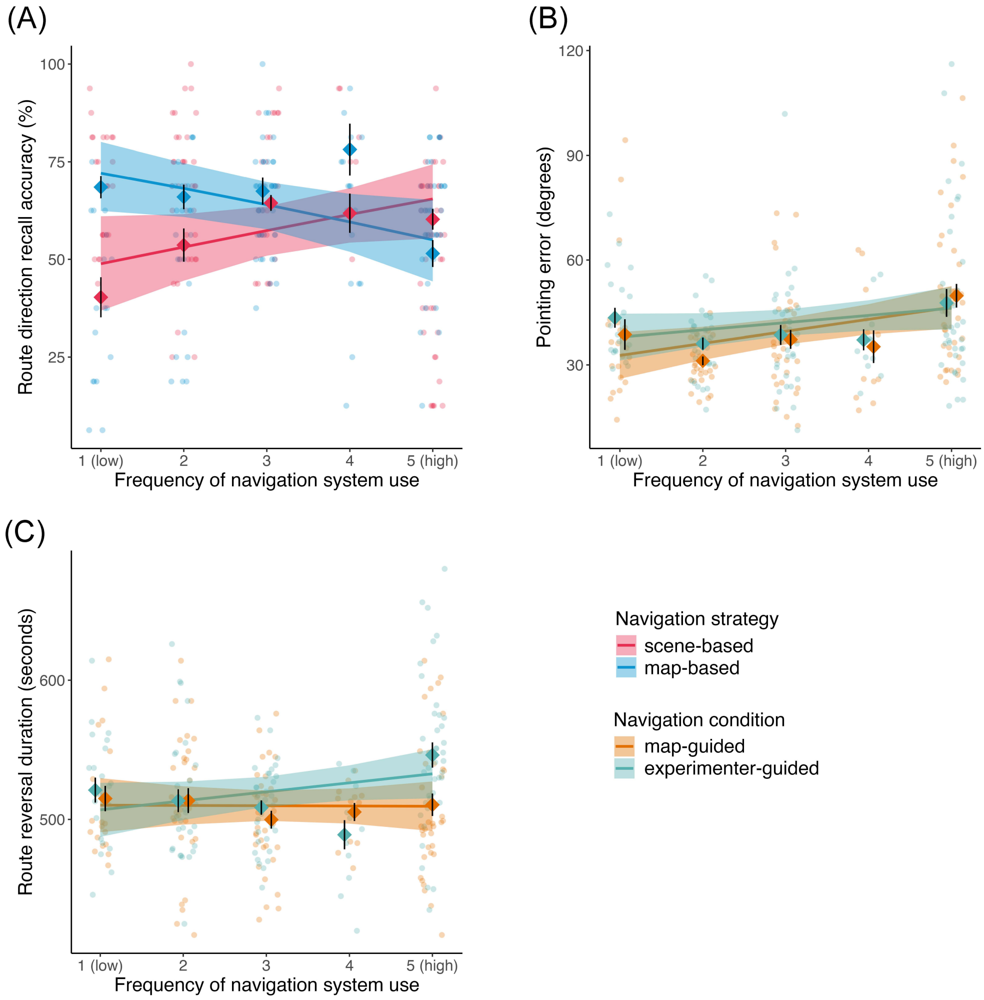

Figure 2 (A) The frequency of navigation system use was negatively associated with route direction recall accuracy among participants who preferred a map-based navigation strategy, but not among those who preferred a scene-based navigation strategy. (B) The frequency of navigation system use significantly predicted pointing error only in the map-guided condition. (C) The negative effect of navigation system use frequency on route reversal performance appeared to be more pronounced in the experimenter-guided condition. However, the association between navigation system use frequency and route reversal duration was not significant in either the map-guided or experimenter-guided condition. Error bars represent standard errors, and shaded areas indicate 95% confidence intervals. Data points were jittered along the x-axis to reduce overlap.

therefore impair navigators' ability to acquire survey knowledge from both the environment and maps, leading to poorer pointing performance, particularly in the map-guided condition where maps were available. This may explain the pattern shown in Figure 2B, where the smaller pointing error in the map-guided condition compared to the experimenter-guided condition observed among participants with lower navigation system use frequency disappears for those with higher use frequency. For navigators who preferred a map-based navigation strategy, habitual use of navigation systems not only impaired their survey knowledge acquisition, but also hindered route knowledge acquisition. One possible explanation is that these individuals typically rely on allocentric processing to encode route information. However, this strategy may be underutilized during habitual navigation system use, resulting in a decline in route learning.

An alternative explanation for the findings in Figure 2B is that navigators who use navigation systems less frequently may possess higher spatial ability, making them more proficient at acquiring allocentric cues directly from maps [5], and thus better positioned to benefit from map availability in the map-guided condition. Consequently for these individuals, differences in pointing performance between the map-guided and experimenter-guided conditions may be more pronounced.

5 Conclusion and future work

This empirical outdoor navigation study conducted in an urban environment indicates that long-term reliance on GNSS-based pedestrian navigation systems negatively influences the ability in route knowledge acquisition, but only for users who employ a map-based navigation strategy. Such reliance is also associated with reduced ability to acquire survey-level direction knowledge, but only during mobile map-assisted navigation. These findings enhance our understanding of how reliance on pedestrian navigation systems can impair users' spatial learning and shed light on the moderating roles of individual navigation strategies and navigation conditions in this relationship.

One limitation of this study is the relatively small sample size, which makes it difficult to cover participants across a broader range of ages, occupations, living in different cities, etc. Furthermore, we assessed participants' reliance on navigation systems with a single, self-reported question, and only considered pedestrian navigation systems. Future research could further explore comprehensive assessments of participants' use of different types of navigation systems (e.g., in-car navigation systems) and quantifying their habits over different time periods (i.e., the last year, the last ten years, etc.). Moreover, recording usage data directly from participants' personal mobile devices (e.g., smartphones) would allow for a more accurate measurement of navigation system use and provide deeper insight into how these systems are employed in daily life.

References

1 Eran Ben-Elia. An exploratory real-world wayfinding experiment: A comparison of drivers' spatial learning with a paper map vs. turn-by-turn audiovisual route guidance. *Transportation Research Interdisciplinary Perspectives*, 9:100280, March 2021. doi:10.1016/j.trip.2020.100280.

2 Iva K. Brunec, Buddhika Bellana, Jason D. Ozubko, Vincent Man, Jessica Robin, Zhong-Xu Liu, Cheryl Grady, R. Shayna Rosenbaum, Gordon Winocur, Morgan D. Barense, and Morris Moscovitch. Multiple scales of representation along the hippocampal anteroposterior axis in humans. *Current Biology*, 28(13):2129–2135.e6, July 2018. doi:10.1016/j.cub.2018.05.016.

3 Louisa Dahmani and Véronique D. Bohbot. Habitual use of gps negatively impacts spatial memory during self-guided navigation. *Scientific Reports*, 10(1), April 2020. doi:10.1038/s41598-020-62877-0.

4 Iveta Fajnerová, David Greguš, Jaroslav Hlinka, Tereza Nekovářová, Antonín Škoch, Tomáš Zítka, Jan Romportl, Eva Žáčková, and Jiří Horáček. Could prolonged usage of gps navigation implemented in augmented reality smart glasses affect hippocampal functional connectivity? *BioMed Research International*, 2018:1–10, June 2018. doi:10.1155/2018/2716134.

5 Chuanxiuyue He and Mary Hegarty. How anxiety and growth mindset are linked to navigation ability: Impacts of exploration and gps use. *Journal of Environmental Psychology*, 71:101475, October 2020. doi:10.1016/j.jenvp.2020.101475.

6 Mary Hegarty, Chuanxiuyue He, Alexander P. Boone, Shuying Yu, Emily G. Jacobs, and Elizabeth R. Chrastil. Understanding differences in wayfinding strategies. *Topics in Cognitive Science*, 15(1):102–119, January 2022. doi:10.1111/tops.12592.

7 Toru Ishikawa. Satellite navigation and geospatial awareness: Long-term effects of using navigation tools on wayfinding and spatial orientation. *The Professional Geographer*, 71:197–209, 2019. doi:10.1080/00330124.2018.1479970.

8 Tobias Meilinger, Julia Frankenstein, Katsumi Watanabe, Heinrich H. Bülthoff, and Christoph Hölscher. Reference frames in learning from maps and navigation. *Psychological Research*, 79(6):1000–1008, November 2014. doi:10.1007/s00426-014-0629-6.

9 Renato Orti, Tina Iachini, Eleonora D'Agostino, Francesco Ruotolo, and Gennaro Ruggiero. Cognitive load in switching between egocentric and allocentric spatial frames of reference: a pupillometry study. *Scientific Reports*, 15(1), July 2025. doi:10.1038/s41598-025-11122-7.

10 Ian T. Ruginski, Sarah H. Creem-Regehr, Jeanine K. Stefanucci, and Elizabeth Cashdan. Gps use negatively affects environmental learning through spatial transformation abilities. *Journal of Environmental Psychology*, 64:12–20, August 2019. doi:10.1016/j.jenvp.2019.05.001.

11 Wilson P. Tanner and John A. Swets. A decision-making theory of visual detection. *Psychological Review*, 61:401–409, November 1954. doi:10.1037/H0058700.

12 Emre Yavuz, Chuanxiuyue He, Christoffer J. Gahnstrom, Sarah Goodroe, Antoine Coutrot, Michael Hornberger, Mary Hegarty, and Hugo J. Spiers. Video gaming, but not reliance on gps, is associated with spatial navigation performance. *Journal of Environmental Psychology*, 96:102296, June 2024. doi:10.1016/j.jenvp.2024.102296.

13 Qi Ying, Weihua Dong, and Sara Irina Fabrikant. How do in-car navigation aids impair expert navigators' spatial learning ability? *Annals of the American Association of Geographers*, 114:1483–1504, 2024. doi:10.1080/24694452.2024.2356858.