Capturing Environmental Scale Spatial Cognition in Applied Settings: A Field Based Pilot with Firefighters

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Abstract

Understanding how spatial knowledge is organized and used across real-world tasks remains an important challenge in spatial cognition research. This paper presents a pilot test of SPaRKS, a framework developed to capture cognitive map accuracy, route decision making, verbalized navigation strategies, GPS use, and navigational value across a dynamic set of cartographic tasks and questionnaires. Using firefighters as an applied pilot group (n=24), we examine whether the tool can capture both route attribute tradeoffs and broader variation in spatial knowledge across individuals and groups. Results indicate that route choice was shaped primarily by distance and steep grades, suggesting that participants did not rely on shortest-path logic alone, but instead weighed practical roadway characteristics when making routing decisions. The pilot also identified meaningful variation across multiple spatial measures, indicating that SPaRKS can move beyond isolated task performance to support the development of integrated spatial profiles. Taken together, this preliminary study illustrates that SPaRKS is a viable framework for examining environmental scale spatial knowledge in applied settings. More broadly, the paper demonstrates the value of a multimodal approach for studying how spatial knowledge is organized and used across route decisions, cognitive map tasks, and self-reported navigation tendencies.

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1 Introduction

Spatial abilities help us do everything from locating apps on our smartphones, to finding our way around a new building or city. These fundamental cognitive tools include our ability to find our way, understand perspective and scale, develop cognitive maps [12], and estimate distances [8] (among others). As technology accessibility and computing power increase, we have the opportunity to study these abilities in more detail than ever before.

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Much spatial cognition research has relied on controlled tasks and non-operational samples, and often at figural or vista scale [19]. While laboratory settings provide important and controlled empirical work on topics such as spatial orientation, perspective taking, and navigation [13, 8, 23, 20], complementary field based approaches can help examine how people perform these tasks in everyday contexts and at environmental scale [12, 5, 1]. However, capturing environmental spatial knowledge in applied settings can be problematic. Nonetheless, measuring a variety of spatial abilities and wayfinding inclinations outside of the laboratory, in real world settings, allows for environmental scale measurement and expands our research participants to a larger group of individuals, since they are not required to attend our laboratories. The purpose of this study is to develop and pilot a novel instrument for extracting and analyzing the structure of cognitive spatial knowledge in field based settings.

While many tools exist to measure spatial ability in laboratory settings, few methods capture the complexity of real-world navigation, environmental familiarity, and decision making in a professional high-stakes setting. To overcome these challenges, a multipart instrument was designed and deployed on tablet computers. The Spatial and Representational Knowledge Survey (SPaRKS) utilizes a standard tablet with internet connectivity to capture these data. The SPaRKS instrument measures spatial thinking through 3 main tasks: (1) a pin-drop mapping exercise to elicit cognitive representations of spatial layouts; (2) a turn-by-turn direction task to investigate participant spatial strategies; and (3) a discrete choice task to assess the physical attributes that are given priority in route selection (e.g. selecting routes based on if they contain steep gradients, have a tight turn radius, or are the shortest distance). In addition to these tasks, the instrument also collects self-report data on sense of direction, the value placed on navigation, GPS use, and demographics. Taken together these tasks demonstrate how this integrated instrument can reveal spatial reasoning processes that are often difficult to measure, especially in applied settings. To demonstrate the capability of SPaRKS, a pilot study was conducted with firefighters in a municipal fire department in Southern California.

2 Background

Studying environmental scale spatial cognition broadens our understanding beyond traditional research populations and includes those who make spatial decisions in high-stakes environments, such as firefighters. Further, environmental scale spatial cognition helps us connect laboratory findings to how spatial cognition is expressed in navigation relevant environments. Studies of individual differences in navigation and spatial cognition reveal that some people exhibit a stronger ability to develop knowledge of places than others [12, 2], and that strategies for doing so also differ [7, 20].

Many real-world navigation problems occur at environmental scale, where decisions happen in relation to routes, constraints, and local context. Environmental scale decisions, like many spatial cognition processes, are influenced by both more objective spatial abilities as well as more subjective spatial inclinations. Capturing objective spatial ability has been done using a variety of instruments, the Money Road Map test [18], the Spatial Orientation Test [10], Silcton [23], and Sea Hero Quest [21], among others.

Subjective measures of spatial cognition are also valuable in understanding spatial behaviors and decision making. Individual self-assessment of sense of direction correlates highly with objective spatial performance [9]. Frequent use of navigation systems has been linked to weaker spatial performance, including lower self-reported sense of direction and greater reliance on route-based strategies [11, 17]. Similarly, a recent meta-analysis found that GPS use was negatively correlated with both sense of direction and environmental knowledge [17]. However, GPS use is dynamic and nuanced, some may use it for gathering information, such as checking traffic, locating a nearby service, or planning a route, while others may use it for turn-by-turn directions [22]. More research is needed to understand the directional relationship of many of these constructs, nonetheless they provide insight into how spatial decisions are executed.

Previous research has found that route decision making does not always result in taking the shortest path [3], the clearly marked path, or the path with rich details [24], which can lead to delays that are at best annoyances and at worst detrimental to life and health. Refining our understanding of how route decisions are made in real-world contexts can help emergency managers better plan evacuation routes, ease traffic congestion, defend pedestrian safety, and allow emergency responders to plan responses more effectively.

3 Methods

SPaRKS is comprised of objective measurement tasks, subjective wayfinding inclination questionnaires, and demographic data collection. Participants are presented with a customized map of an environment that is familiar to them which contains building footprints without names, streets but no street names, and at least 2 named landmarks to help them situate the scale and layout of the map. Next, they are presented with an address and asked place a digital map-pin onto the map where they think that address is located. Correctness is determined by both context and a GIS calculated buffer zone. The address selection task has 4 individual addresses, each presented one at a time.

Next, participants are presented with another set of addresses, one at a time, and asked to write out how they would route to that address given a predetermined starting point. The written directions portion contains 6 addresses. These written routes are transcribed onto maps in a GIS and a similarity analysis is run. Further, the routes are also qualitatively analyzed using content analysis [6] to explore how their spatial language is related to their strategy and performance [14].

Finally, participants are presented with one screen that contains 3 maps panels, each panel contains a different route between a single starting point and a destination. The maps featured local streets and street names familiar to the participants but excluded details such as traffic or topography. This design explicitly required participants to synthesize the visual map prompt with their existing internal cognitive maps of the response district. Participants are asked to choose which route they would take if they were trying to get to the destination the fastest. Participants are presented with 6 total route-choice questions. These data are compiled and analyzed following discrete choice analysis via multinomial logit regression, with consideration of physical route characteristics (length of the route, number of turns, and steepness of the road grade) as well as the source of the route (Figure 1). Note that, firefighter navigation training in the United States is non-uniform; departments predominantly rely on informal methods like map memorization, street-identification games, and district driving [16]. Consequently, the map tasks used in this pilot study (pin-drop, turn-by-turn description, and route selection) are not established methods for how firefighters typically learn their response areas.

The routes and destinations used in SPaRKS were chosen to represent different levels of difficulty. To achieve varying levels of difficulty, the Route Choice Scenario Builder was developed in RStudio using the Shiny package [4] to assist with categorizing difficulty.

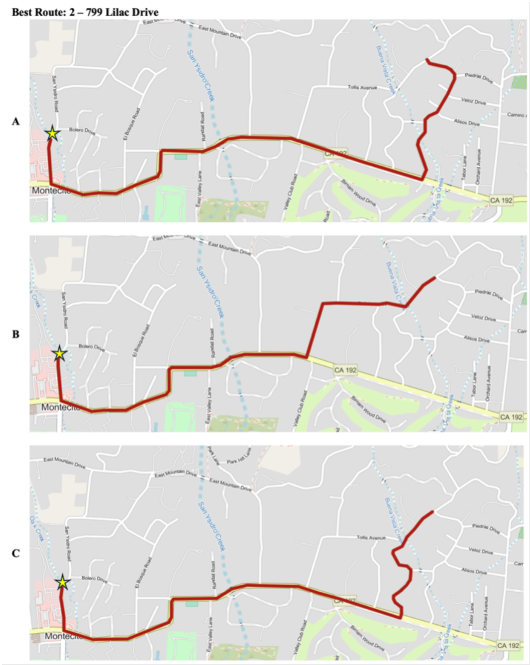

Figure 1 An example of one of the 3 maps panels presented to particpants for the route choice questions.

SPaRKS also captures self-report measures of spatial cognition including the Santa Barbara Sense of Direction scale (SBSOD) [9], value placed on navigation, and the GPS use questionnaire [22]. Participants are also given a demographic questionnaire to capture their age, gender, education level, and other applicable details.

4 Procedure

To assess the functionality of SPaRKS, it was pilot tested with a municipal fire department in Southern California. A total of 24 male firefighters (average age 42 years) participated in the study while on duty. SPaRKS was delivered on iPad tablets with internet connectivity at their respective firehouses. The researcher introduced the topic, explained the procedure and asked the participants to work alone on their survey. Participants were instructed to ask questions if they were not clear on the procedure, and the researcher remained in the room with the participants during data collection. At the end of each set of data collection, the firefighters provided feedback on the survey and were given the opportunity to ask questions about the project. They were instructed to not give any tips or other survey information to the other firefighters that were not on shift at the present data collection visit. In total data collection was completed over 5 visits to the firehouses.

5 Results

SPaRKS identified patterns in route selection that illustrate how participants prioritize route characteristics such as grade, number of turns, and length, features that would be difficult to capture through surveys alone. Each participant was presented with 6 destinations for the route choice task, which was designed to elucidate spatial decision making and identify preferable route attributes. The focus here is on the route-choice findings because they most directly showcase SPaRKS ability to capture operational spatial decision making.

Multinomial logit modeling on physical route characteristics identified that route length and the presence of steep grades were significant predictors of route choice. For each 1-mile increase in route length, the odds of that route being selected decreased by 65%, and if the route contained a steep grade the odds of selecting it dropped by 94%. Number of turns was not a statistically significant predictor (Table 1). Analysis of utility tradeoffs for how distance influenced choice, specifically how much participants were willing to travel to reduce the number of turns or avoid steep grades, found that on average, participants were willing to add 2.69 miles onto their route if it avoided steep grades, while number of turns did not reach significance. (Table 1).

Table 1 Route Attributes; multinomial logit model.

Predictor	β	Robust SE	Odds Ratio	95% CI	p
Distance (miles)	-1.05	0.32	0.35	[0.19, 0.66]	0.001
Number of Turns	0.10	0.10	1.10	[0.90, 1.34]	0.34
Steep grade	-2.83	0.82	0.06	[0.01, 0.29]	$< .001$

Note. ***β = coefficient; OR = odds ratio***

Overall, these findings suggest that firefighters did not simply rely on shortest-path logic when selecting routes. Instead, route choice reflected practical tradeoffs tied to roadway suitability, with distance remaining important, but steep grades also shaping what routes were seen as preferable. Although source was also related to route choice, these differences appear to be driven primarily by the physical characteristics of the routes themselves.

SPaRKS was able to capture individual variation in cognitive map accuracy, route selection, verbalized navigation strategies, GPS use, and the value individuals place on navigation. Findings from this pilot test suggest that SPaRKS goes beyond isolated task performance and provides data that can be compiled into an integrated spatial profile, offering a way to capture multidimensional variation in spatial knowledge. An integrated spatial profile shifts the focus away from a singular spatial knowledge type, or simply asking who is a "good navigator," and instead toward a more complete understanding of what kinds of spatial knowledge and strategies are present within a person or group.

To explore the creation of an integrated spatial profile, performance was compared across the components of SPaRKS [15]. Firefighters holding the rank of Engineer (driver/operator) performed stronger than other ranks, particularly in the pin-dropping task and on the GPS use questionnaire, while those with more experience also showed less pin-drop error, lower GPS use, and stronger navigational value scores. Taken together, these findings suggest that SPaRKS is sensitive not only to route decision making, but also to broader differences in how spatial knowledge is organized and used across individuals.

6 Discussion

Within the fire service, these data offer immediate insights into who needs more training, assess whether their current navigation training is effective, and isolates firefighters for promotion into the engineer (driver/operator) position. During post data collection discussions with the firefighters who participated in the pilot, many expressed interest to know how well they performed across the tasks. Further, the department leadership requested aggregate data to systematically rectify training deficiencies and refine processes. Beyond the scope of the fire service, SPaRKS could be a useful tool for other emergency responders such as police, emergency medical providers, as well as search and rescue teams, where high-stakes and time sensitive response is critical to the outcome.

SPaRKS also shows utility outside emergency responders, with application into the evaluation of groups such as novice or elderly drivers, commercial delivery couriers, drone pilots, or orienteering competitors. These groups could provide broader insight into the development and decline of spatial abilities. Such research would clarify how specific operational demands intersect with spatial cognition, whether managing the 2D-to-3D perspective shifts required of drone operators, the race pressure experienced by competitive athletes, or the temporal pressures faced by emergency responder professionals trained to handle time-sensitive and high-stakes responses.

This study provides evidence that SPaRKS can extend and complement laboratory based spatial cognition research toward a more applied understanding of how people know, reason through, and move across real environments. Future work should utilize more participants, and include a more heterogeneous sample with regards to age, gender, and profession.

7 Conclusion

This preliminary study illustrates that SPaRKS is a useful tool for capturing field based spatial cognition across a variety of tasks. Rather than isolating spatial knowledge through a single task, SPaRKS was able to capture variation in cognitive map accuracy, route decision making, verbalized navigation strategies, GPS use, and navigational value. Importantly, these patterns were not random; they varied in meaningful ways with familiarity, experience, and operational role, suggesting that SPaRKS is sensitive to real-world differences in how spatial knowledge is organized and used. The route choice findings further indicate that field based approaches can capture spatial decision making in context, including the tradeoffs individuals make between distance, roadway characteristics, and operational suitability.

Overall, this pilot study provides initial evidence that SPaRKS is a viable framework for exploring environmental scale spatial cognition in applied settings. By integrating multiple forms of spatial data, SPaRKS offers a way to connect controlled spatial cognition research to the applied context in which navigation and route decisions unfold.

References

1 C. Bae, D. Montello, and M. Hegarty. Wayfinding in pairs: Comparing the planning and navigation performance of dyads and individuals in a real-world environment. *Cognitive Research: Principles and Implications*, 9(1):40, 2024. doi:10.1186/s41235-024-00563-9.

2 A. P. Boone, B. Maghen, and M. Hegarty. Instructions matter: Individual differences in navigation strategy and ability. *Memory & Cognition*, 47(7):1401–1414, 2019. doi:10.3758/s13421-019-00941-5.

3 M. L. Brachman, R. Church, B. Adams, and D. Bassett. Wayfinding during a wildfire evacuation. *Disaster Prevention and Management*, 29(3):249–265, 2020. doi:10.1108/DPM-07-2019-0216.

4 W. Chang, J. Cheng, J. Allaire, et al. *shiny: Web Application Framework for R*, 2024. R package version 1.10.0. URL: https://CRAN.R-project.org/package=shiny.

5 E.-M. Griesbauer, E. Manley, J. M. Wiener, and H. J. Spiers. London taxi drivers: A review of neurocognitive studies and an exploration of how they build their cognitive map of London. *Hippocampus*, 32(1):3–20, 2022. doi:10.1002/hipo.23395.

6 I. Hay and M. Cope, editors. *Qualitative research methods in human geography*. Oxford University Press, 5th edition, 2021.

7 M. Hegarty, C. He, A. P. Boone, et al. Understanding differences in wayfinding strategies. *Topics in Cognitive Science*, 15(1):102–119, 2023. doi:10.1111/tops.12592.

8 M. Hegarty, D. R. Montello, A. E. Richardson, et al. Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence*, 34(2):151–176, 2006. doi:10.1016/j.intell.2005.09.005.

9 M. Hegarty, A. E. Richardson, D. R. Montello, et al. Development of a self-report measure of environmental spatial ability. *Intelligence*, 30(5):425–447, 2002. doi:10.1016/S0160-2896(02)00116-2.

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 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.

12 T. Ishikawa and D. R. Montello. Spatial knowledge acquisition from direct experience in the environment. *Cognitive Psychology*, 52(2):93–129, 2006. doi:10.1016/j.cogpsych.2005.08.003.

13 M. Kozhevnikov and M. Hegarty. A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition*, 29(5):745–756, 2001. doi:10.3758/BF03200477.

14 T. P. McNamara, J. Sluzenski, and B. Rump. Human spatial memory and navigation. In *Learning and Memory: A Comprehensive Reference*, pages 157–178. Elsevier, 2008. doi:10.1016/B978-012370509-9.00176-5.

15 C. McWhorter. *Navigation & Spatial Cognition in the US Fire Service*. PhD thesis, University of California, Santa Barbara, 2025. URL: https://escholarship.org/uc/item/4586s2vj.

16 C. McWhorter, M. Hegarty, K. Baylis, et al. Mapping the response: A survey of municipal firefighter navigation training and practices in the United States. *International Journal of Disaster Risk Reduction*, 123:105446, 2025. doi:10.1016/j.ijdrr.2025.105446.

17 L. Miola, V. Muffato, E. Sella, et al. GPS use and navigation ability: A systematic review and meta-analysis. *Journal of Environmental Psychology*, page 102417, 2024. doi:10.1016/j.jenvp.2024.102417.

18 J. Money, D. Alexander, and H. T. Walker. *A Standardized Road Map Test of Direction Sense*. Johns Hopkins Press, 1967.

19 D. R. Montello. Scale and multiple psychologies of space. In *Spatial Information Theory A Theoretical Basis for GIS*, volume 716, pages 312–321. Springer, 1993. doi:10.1007/3-540-57207-4_21.

20 V. Muffato, L. Miola, M. Pellegrini, et al. Investigating the different domains of environmental knowledge acquired from virtual navigation. *Cognitive Research: Principles and Implications*, 8(1):50, 2023. doi:10.1186/s41235-023-00506-w.

21 H. J. Spiers, A. Coutrot, and M. Hornberger. Explaining world-wide variation in navigation ability from millions of people: Citizen science project Sea Hero Quest. *Topics in Cognitive Science*, 15(1):120–138, 2023. doi:10.1111/tops.12590.

22 A. Topete, C. He, J. Protzko, et al. How is GPS used? understanding navigation system use and its relation to spatial ability. *Cognitive Research: Principles and Implications*, 9(1):16, 2024. doi:10.1186/s41235-024-00545-x.

23 S. M. Weisberg, V. R. Schinazi, N. S. Newcombe, et al. Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 40(3):669–682, 2014. doi:10.1037/a0035261.

24 J. Wilkening and S. I. Fabrikant. How do decision time and realism affect map-based decision making? In *Spatial Information Theory*, pages 1–19. Springer, 2011. doi:10.1007/978-3-642-23196-4_1.