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Cognitive Maps: Some People Make Them, Some People Struggle

Steven M. Weisberg[1] **and Nora S. Newcombe**[2]
[1]Center for Cognitive Neuroscience, University of Pennsylvania, and
[2]Department of Psychology, Temple University

Abstract

The proposal that humans can develop cognitive maps of their environment has a long and controversial history. We suggest an individual-differences approach to this question instead of a normative one. Specifically, there is evidence that some people derive flexible maplike representations from information acquired during navigation, whereas others store much less accurate information. Our research uses a virtual-reality paradigm in which two routes are learned and must be related to each other. It defines three groups: integrators, nonintegrators, and imprecise navigators. These groups show distinctive patterns of spatial skills and working memory, as well as personality. We contrast our approach with research challenging the cognitive-map hypothesis and offer directions for rapprochement between the two views.

Keywords

cognitive maps, spatial navigation

All mobile species must find their way around the world to survive and reproduce. Wide-ranging comparative research shows that evolved navigation systems exhibit significant commonalities across species but also reveals interesting differences not only due to variations in sensory capacities but also due to varied evolutionary pressures (e.g., Rosati & Hare, 2012; Wiener et al., 2011). Tolman (1948) highlighted cross-species commonality in writing about "cognitive maps in rats and men," showing regrettable word choice in using the noun "men," but also launching a controversy about cognitive maps that continues to this day. The cognitive-map view of navigation is that it involves representing space in an allocentric format that allows recovery of distances and directions between locations and flexible planning of routes (Gallistel, 1989; O'Keefe & Nadel, 1978). This view is widely endorsed by rodent neurophysiological researchers who study neurons that code spatial properties such as location (place cells), orientation (head direction cells), boundaries (border cells), and distance (grid cells). Recent neuroimaging work has supported the existence of many of these same properties in the human brain (for a review, see Epstein, Patai, Julian, & Spiers, 2017). An alternative view is that rodents and humans simply rely on snapshot memories of locations and route-following response strategies for navigation (e.g., Shettleworth, 2010; Warren, Rothman, Schnapp, & Ericson, 2017). We have argued recently that this debate may admit of a simple solution. People differ considerably in their ability to learn large-scale environments and navigate within them (Hegarty & Waller, 2005; Wolbers & Hegarty, 2010). Thus, some participants in experiments may encode accurate internal maps, and others may encode spatial information imperfectly or in fragments or rely entirely on route-based strategies.

Route Integration in the Real World

The individual-differences approach to navigation began with research by Ishikawa and Montello (2006), who devised a testing method called the *route-integration paradigm*. Participants experience two separated routes and try to learn the names and locations of distinctive places (such as buildings). Later, they experience a connecting route. People in Ishikawa and Montello's experiment, who were driven by the

Corresponding Author:
Nora S. Newcombe, Temple University, Department of Psychology, 1701 N. 13th St., Weiss Hall, 6th Floor, Philadelphia, PA 19122
E-mail: newcombe@temple.edu

experimenter around the hills above Santa Barbara, California, on successive days, differed dramatically in what they learned. Some people related the two routes effectively, immediately, and seemingly easily. Some people learned to relate the routes over time. Both groups arguably formed cognitive maps, at least eventually. However, some people never integrated the routes, that is, did not ever form a cognitive map.

Because active rather than passive movement might facilitate spatial learning, Schinazi, Nardi, Newcombe, Shipley, and Epstein (2013) conducted a very similar experiment but led their participants on a walking tour along two routes and, later, two connecting routes in a campus environment. Like Ishikawa and Montello, Schinazi and colleagues found substantial individual differences, although variation in the walking environment was most marked before participants experienced the connecting route. We also found that perspective-taking skills assessed on a paper-and-pencil test were correlated with individual differences in real-world spatial learning, a relation also found in other studies (Wolbers & Hegarty, 2010).

Route Integration in Virtual Reality

Variation in perspective-taking skills is interesting, but it would be nice to know more about the correlates of individual differences in cognitive mapmaking. A practical challenge to individual-differences research in navigation is that experimentation in a real-world environment poses logistical difficulties, such as cancellations because of bad weather and the necessity to transport participants to unfamiliar areas. Furthermore, we cannot test diverse geographic and cultural populations in a standard real-world environment; transporting all our participants to Santa Barbara or Philadelphia is unrealistic! Especially problematic for individual-differences research, logistical factors limit sample size, making it difficult to gather large enough samples to have the power to probe variation. To address these problems, Weisberg et al. (2014) devised a virtual learning environment modeled after the real-world route-integration paradigm (Fig. 1).

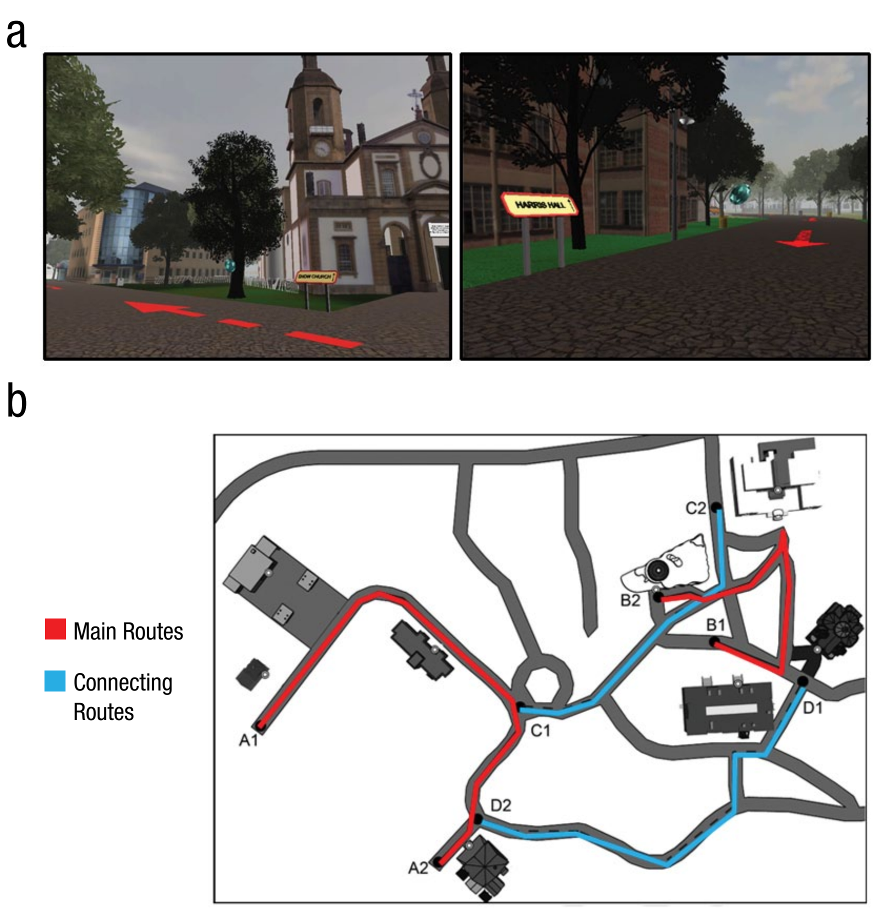

Fig. 1. Screenshots from the Virtual Silcton desktop virtual environment (a) and an overhead map of the area participants "traveled" (b). Buildings are shown in the screenshots, along with signs and blue gems, which indicated the presence of a building nearby. The overhead map shows the locations of the buildings, which participants learned (although this map was never shown to them). White circles represent the front door of each building.

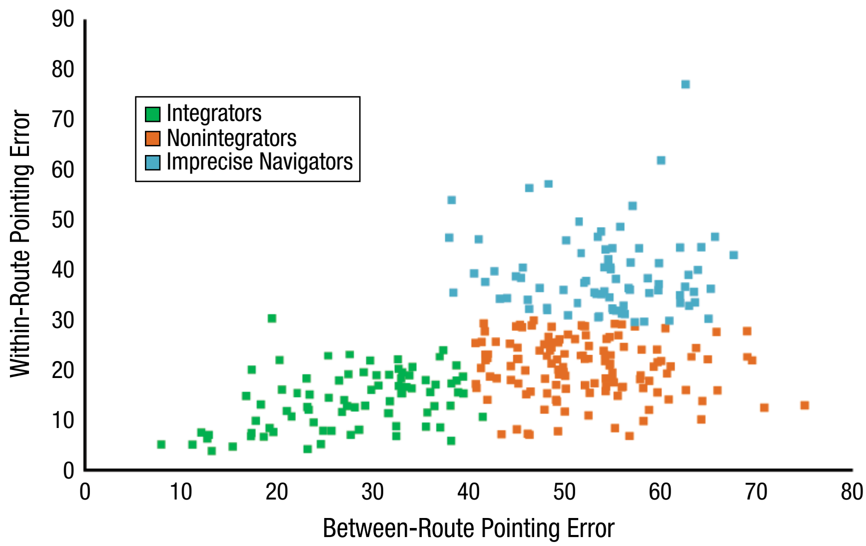

Fig. 2. Scatterplot showing the correlation between performance on the two types of pointing trials from Virtual Silcton. Colors refer to results from cluster analyses, dividing participants into three groups. Between-route pointing trials required participants to point across the two main routes (i.e., from a building along one main route to a building along the other main route). Within-route pointing trials required participants to point within the same main route. Pointing was measured in degrees of error, with 90° as chance performance. Data are from 294 participants from the four studies reported in Weisberg and Newcombe (2016), including the data that were also presented in Weisberg, Schinazi, Newcombe, Shipley, and Epstein (2014).

The virtual environment had the same spatial configuration as the real-world study (Schinazi et al., 2013) but replaced the buildings with virtual models of similar saliency, size, and style. In the virtual-route-integration paradigm (which we call Virtual Silcton), participants virtually traveled along two routes, which were indicated by arrows along each path, and learned four buildings per route. Then they traveled along two connecting routes, which connected the first two routes. Finally, they completed two navigation tests: an on-site pointing task, in which they were dropped at each building location and had to point to all other buildings, and a model-building task, in which they had to drag and drop building images around a map to recreate the configuration. Crucially, the route-integration paradigm allows us to distinguish between buildings that are traveled between directly because they are learned along the same initial route (within route) and buildings that are never directly traveled between (between route). The connecting routes provide a path between segments of the two routes, but inferences must still be made about how the buildings along the two routes relate to each other overall. As a result, between-route judgments require much more difficult spatial inferences.

Individual differences emerged for both within- and between-route judgments, and a cluster analysis based on between- and within-route pointing scores suggested the existence of three groups[1] (Fig. 2). One group, integrators, performed well on both within- and between-route judgments. A second group, nonintegrators, performed well on within-route judgments but relatively poorly on between-route judgments. A third group, imprecise navigators, performed relatively poorly (although above chance) on both types of pointing judgments. These results, which we have now replicated across four separate samples in two published studies (Weisberg & Newcombe, 2016; Weisberg et al., 2014), suggest a two-step process in which routes are learned first and then related to each other.

Cognitive Correlates

A key question is whether individual differences on these aspects of learning an environment are mirrored by individual differences in related aspects of cognition. We have now investigated whether the three groups of navigators show distinct patterns of performance on related tasks, both in the spatial domain and in terms of domain-general cognitive abilities.

In terms of spatial cognition, it is important to remember that it is a variegated domain, not a monolithic one (Newcombe, 2018). Some common tests of spatial ability are conceptually and empirically linked to large-scale navigation, while other tests seem to tap small-scale spatial tasks and depend on somewhat different neural systems. The widely used mental rotation test (MRT; Vandenberg & Kuse, 1978), wherein participants must match an object made up of cubes with its rotated equivalents, is likely a measure of small-scale spatial ability. However, despite its conceptual distinctness, MRT performance varied across the three Silcton groups: Integrators outperformed nonintegrators, who outperformed imprecise navigators (Weisberg & Newcombe, 2016). Perspective taking is more closely related to navigation (Lambrey, Doeller, Berthoz, & Burgess, 2011), and data from Schinazi et al.'s (2013) real-world study of navigation revealed a strong relationship between perspective-taking ability and navigation performance. Recently, in a study of children and adolescents, Nazareth, Weisberg, Margulis, and Newcombe (2018) found that perspective taking accounted for a wider range of navigational behaviors in Virtual Silcton than mental rotation and more variance when included in regression equations along with MRT ability. Thus, the correlation with MRT ability may reflect shared variance between MRT ability and perspective taking rather than mental rotation per se.

In terms of domain-general cognitive capacities, integrators and nonintegrators both outperform imprecise navigators on verbal and spatial working memory measures. This fact suggests that a general working memory capacity might underlie the ability to store navigationally relevant data. Learning within-route relations has both verbal and spatial components, including remembering the associations among the names of buildings, the appearance of the buildings, and the buildings' locations. However, different aspects of spatial working memory may relate to integrating two routes in a large-scale environment as well as to within-route learning (Blacker, Weisberg, Newcombe, & Courtney, 2017). Importantly, these results were obtained with a statistical control for general intelligence, and the three groups did not differ substantially in *g*, although imprecise navigators were significantly worse than the other two groups when the data from several studies were aggregated (Weisberg & Newcombe, 2016).

Ability Versus Preference

There is another approach to individual differences in navigation that emphasizes flexibility in the application of navigation strategies (Shelton, Marchette, & Furman, 2013). This task, called the *dual-solution paradigm*, taps navigation strategy and preferences in a virtual maze (i.e., whether individuals prefer a place-based or response-based approach to navigation; Marchette, Bakker, & Shelton, 2011). Navigators must learn to locate a set of objects in a maze but can find them using a learned familiar route or using a novel shortcut. We have administered the dual-solution paradigm as well as Virtual Silcton to assess whether the conceptualizations are the same or different. Our data suggest that integrators can be successful with either navigation strategy, whereas imprecise navigators are successful only if they use the route-based strategy.

In addition, integrators and nonintegrators seem to store knowledge about Virtual Silcton in a way that would support multiple strategies. Specifically, when we asked Silcton participants whether buildings were first encountered on the same route or on different routes, we found that integrators performed as well as nonintegrators. If integrators formed a global cognitive map and disregarded the route knowledge (i.e., which buildings were along which routes) as irrelevant to learning the whole environment, they would have performed worse on this task. Instead, this suggests that integrators built on strong knowledge of both routes to integrate the two together.

Motivational and Emotional Correlates

One possibility that could explain the individual differences we see in Silcton results is that some navigators have different motivational or emotional dispositions or different personalities. Let us take motivation first. Some people might worry that imprecise navigators just do not try very hard to succeed at the task. However, we do not think that is the case, because we ran a version of the Silcton study (Study 3, Weisberg & Newcombe, 2016) in which we told participants they would be entered in a bonus raffle if they finished in the top half of all participants. Performance was not measurably improved by this incentive, and the same pattern of three groups still emerged.

What about emotion, especially anxiety? It is natural to wonder whether imprecise navigators may simply be fearful and apprehensive about navigating. Anxiety about doing mathematics drains working memory and lowers math performance (Beilock, 2008), so navigation could be a similar case. Indeed, across several studies, imprecise navigators scored higher on a spatial anxiety self-report measure, which assesses how fearful and apprehensive people feel in various navigational situations. But we need to remember that a correlation can run two ways. Spatial anxiety is also negatively correlated with self-ratings of navigation proficiency on the Santa Barbara Sense of Direction (SBSOD) Scale (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002). Similarly, the SBSOD is correlated with high emotional stability on the Big Five personality test, that is, with low anxiety, withdrawal, and self-consciousness (Condon et al., 2015). Thus, anxiety about navigation may impede success, but the alternative is that people may simply be anxious about performing a task that they are aware they do poorly.

What about personality? Perhaps integrators are good navigators because they are adventurous and relish the challenge of learning a new environment. Interestingly, ratings on the SBSOD are related to Openness on the Big Five personality test, which is a measure of curiosity, ingenuity, and adventurousness, and to Extraversion, which measures energy, enthusiasm, and approach behavior (Condon et al., 2015). In addition, Condon et al. found that SBSOD ratings are related to Conscientiousness, which measures attention to detail, organization, and diligence. These data paint a picture of integrators as both eager to learn and willing to work hard at cognitive tasks, underscoring the idea that forming cognitive maps is possible but not automatic or effortless.

Status of the Cognitive-Map Controversy

We see two possible issues in assigning spatial representations to the brain in the form of a cognitive map. First, what is meant by "map"? Here, we define a map as a recording of metric associations among properties of the world. This recording can be on paper (traditional maps), digitally instantiated (GPS displays), or in the brain (a cognitive map). Note that maps need not be veridical—even in physical maps, all transformations of a sphere onto a plane will introduce distortion. Maps can also be distorted for other reasons (e.g., through errors in recording or to emphasize certain features, such as enlarge a landmark). Introducing systematic distortions of the metric content changes the representation of space from a map to what we would call a schematic. A schematic retains some metric associations (e.g., directions) but systematically changes others, as in a subway map.

The second possible issue is how the brain instantiates a map. The term "cognitive map" has been criticized for implying a completely unified representation in which all possible spatial relations are represented equivalently (Downs, 1981). Indeed, Warren et al. (2017) have recently argued that there can be no cognitive map, because human cognition exhibits distortions, which mean the underlying representation must be non-Euclidean. In their study, participants had no trouble with wormholes in virtual environments. The wormholes distort Euclidean space by automatically transporting navigators to bypass a section of the maze. Navigators do not become lost or disoriented (and in fact are perfectly happy to take the wormhole shortcut). Warren et al. argue that because the gaps between wormholes are not represented, the cognitive map must not be Euclidean and therefore is not a map at all. Instead, they claim, human navigation behavior is better characterized by a labeled graph—a mathematical structure by which objects are related through pairwise connections of varying strength. The labels on the graph refer to rough distances and directions between pairs of locations. However, there is recent neuroimaging work showing that the hippocampus has similar representations of locations that are either close together in space or close together as experienced in time (i.e., even through teleporting). This finding suggests that the reason for the distorted metric information may be that the hippocampus normally builds time-dependent representations of space (Deuker, Bellmund, Navarro Schröder, & Doeller, 2016). The lack of a way to take account of wormholes may be an idiosyncrasy of tricking an evolved system built for the natural world by forcing it to try to cope with an environment possible only in virtual reality.

Despite the seeming dichotomy of the "cognitive maps—yes or no" debate, we see areas of commonality. The two descriptions might be reconciled if we postulate that spatial relations in large-scale space exhibit a hierarchical representation, in which local areas, or routes, are represented in detail but the relations among them are represented more coarsely (Chrastil & Warren, 2014; Jacobs & Menzel, 2014; Jacobs & Schenk, 2003; Kuipers, 2000; Wolbers & Hegarty, 2010). In some cases, it makes sense to think of navigable space as a network—a set of connections between locations, with rough information about direction and distance. After learning, this may be how we can navigate in a car in cities with one-way streets. In other cases, it makes sense to think of navigable space as a map with distortions. In an area such as a forest or desert, with few distinct landmarks, we can nevertheless maintain orientation. We think our data on Virtual Silcton provide evidence in support of the idea that some navigators do form cognitive maps. Minimally, they can do something a map affords easily, which a graph does not: They can calculate distances and directions between places to which they have never directly traveled.

Recommended Reading

Waller, D., & Nadel, L. (Eds.) (2013). *Handbook of spatial cognition*. Washington, DC: American Psychological Association. A comprehensive collection of chapters on various topics related to spatial cognition in general and navigation behavior specifically, including chapters on individual differences, computational modeling, animal and human behavior and neuroscience, applications, and the roles of language, perception, and memory in navigation.

Warren, W. H., Rothman, D. B., Schnapp, B. H., & Ericson, J. D. (2017). (See References). An empirical article that outlines the cognitive-graph theory alternative to cognitive-map theory.

Weisberg, S. M., & Newcombe, N. S. (2016). (See References). The largest individual-differences studies we have published using Virtual Silcton, with full methodological details and findings.

Wolbers, T., & Hegarty, M. (2010). (See References). A theoretical approach to individual differences in navigation that breaks down aspects of navigation behavior into cognitive and neural constituents.

Action Editor

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Note

1. It is important to note that 10° to 15° is approximately ceiling performance for pointing judgments and that most integrators and nonintegrators are in or around this range on within-route pointing. This is because small deviations in pointing to the buildings themselves, instead of precisely pointing to the front door, yield degrees of error in that range, despite participants pointing accurately at some part of the building.

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