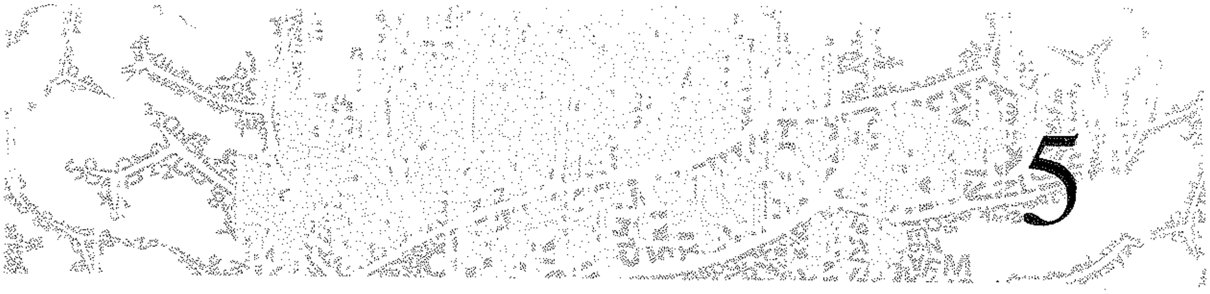

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Spatial Memory: From Theory to Application

Douglas H. Wedell and Adam T. Hutcheson

Spatial memory has been investigated across diverse environments and under numerous cognitive constraints. This research has provided the basis for understanding the cognitive and neural underpinnings of remembering places in space. We review these findings with a particular focus on how they may apply to problems of spatial memory posed by technological advances that are fundamentally changing the way people process spatial information. While there are a myriad of applications tied to spatial memory processing, we primarily consider those linked to technological innovations, as these provide exciting new frontiers for exploration. Before beginning our review, we provide an overview of three technologies of particular interest: 1) the widespread use of virtual environments, 2) the implementation of augmented reality, and 3) the widespread use of global positioning systems.

VIRTUAL ENVIRONMENTS (VEs)

Research on spatial memory has traditionally used real-world settings of various orders of magnitude to test participants' spatial abilities. However, these environments pose problems related to controlling elements of experimental design. It may be difficult to find environments that suit the needs of the study, whether because of size, environmental features, availability, or familiarity. In contrast, VEs, such as those found in video games and military training simulators, provide an excellent testing ground for spatial memory. VEs make it possible to generate completely novel worlds that simulate the kinds of real world environmental features that people encounter without the limitations of those environments. Spatial memory results from VEs tend to be very similar to those from real environments, with the only consistent difference being greater underestimation of distance in VEs compared with real environments (Jansen-Osmann & Berendt, 2002).

Whereas researchers first used VEs for greater experimental control of the environment, the case can now be made that understanding how spatial memory applies to VEs is of inherent interest. This is because VEs are becoming the primary environment we experience in some cases. For example, medical surgery is now guided by VE renditions, as is the piloting of drone planes. Thus, it is important to pay close attention to how VEs are perceived and remembered. Chen and Stanney (1999) have identified many ways that VEs can be used as navigational aids. Importantly, VEs can remove the difficulties of translating information between maps and wayfinding, providing a viewer centered representation to the individual that may facilitate exploration of the environment. As these technologies become more available to the public on a daily basis, it becomes incumbent on researchers to understand navigation through VEs and how their features may best be utilized in aiding spatial memory and navigation.

AUGMENTED REALITY (AR)

An even newer technology that has immediate applications is AR. Mapping the egocentric perspective of environmental object layouts found in VEs onto views of actual environments, AR technology places virtual objects and markers within a real-world viewpoint. This technology allows users to place a virtual marker in an environment and then use the camera on their cellular phone to locate the marker in their visual field. A recent development in AR technology comes from Google in the form of a pair of glasses that overlay information from an on-board computer to aid the user in various tasks. The tool of AR technology brings to the fore the key research question of how verbal and other enhanced information is integrated with spatial information in creating cognitive spatial maps that guide interactions with the environment. Hence, it is important to consider applications of integration of different modalities of information in applications to AR technology.

GLOBAL POSITIONING SYSTEMS (GPS) AND SATELLITE-VIEW MAPS

technology for determining one's position within the environment. People routinely use these devices when navigating in unfamiliar places. GPS devices provide maps that change as one's position changes. GPS units equipped with auditory cues may help people find locations in ways that we could not dream of only a few decades ago (Loomis, Golledge, Klatsky, & Marston, 2007). One exciting application of this research is in aiding visually impaired individuals during wayfinding.

Despite their popularity, there may be drawbacks to using GPS as a means of wayfinding. Ishikawa, Fujiwara, Imai, and Okabe (2008) found that GPS users took longer to navigate, showed more errors, and constructed poorer cognitive maps than traditional map users or individuals who navigated just by using direct experience with the environment. If people are attending to the GPS, they may not be encoding useful information about the environment that is needed for developing accurate spatial memory. Considering the rapid and dedicated infusion of this technology into all aspects of daily life, it will be important to understand how these technically advanced spatial navigation devices can both aid and hinder spatial memory and successful navigation in a complex environment.

BASIC ISSUES AND APPROACHES TO STUDYING SPATIAL MEMORY

Although our approach to the literature is primarily from a psychological viewpoint, there are implications of this research across diverse disciplines, such as geography, anthropology, linguistics, neurosciences, and computer science. We overview these approaches, highlighting key historical trends and issues. In the bulk of our review, we describe contemporary spheres of inquiry divided into four basic themes: 1) the nature

Several recurrent issues will be woven together throughout our discussion of the spatial memory literature. First is the issue of scale: Do the same mechanisms of spatial memory that apply to remembering locations in small spaces also apply to remembering locations in large spaces? Second is how memory is utilized in navigation: How does one update location, estimate distance, and make course corrections? Third is the issue of how to integrate information gathered from different perspectives, egocentric or viewer-centered perspectives and allocentric or map-like representations. Finally, we consider the issue of how analog and categorical representations of spatial information are combined in various spatial memory tasks. As we review the literature, we encourage the reader to consider how the technological advances described above may influence performance in spatial memory tasks in these different ways.

FIELDS RELATED TO SPATIAL MEMORY

In cognitive studies of spatial memory, the key research issues concern the nature of the representation of information and the processes used to encode, retrieve, manipulate, transform, and respond to that information. Other disciplines examine how these processes may apply to specific domains. Geographers have examined the role of spatial cognition and information systems and real-world navigation. For example, they have developed complex digital layered maps that have been used in locating lost persons in forests by law enforcement in an attempt to make the process of navigating unfamiliar areas more efficient (Heth & Cornell, 2007). Linguists have conducted collaborative research examining the links between language and spatial concepts and representations. Linguistic descriptions of spatial relations provide many of the tools for mentally constructing a representation of spatial arrangements and environments (Beirwisch, 1996). The best forms of communicating these relationships may well depend on cultural conventions, as explored within the discipline of anthropology. For example, field anthropologists have shown how human cognitive mapping abilities relate to the hunting of migratory animals (Istomin & Dwyer, 2009).

The neural basis of spatial cognition and memory has long been an important area of research. With the development of neuroimaging techniques, cognitive-neuroscience researchers have made great strides in validating and expanding neural models of spatial cognition and memory developed from comparative research to human spatial cognition (Burgess, Maguire, & O'Keefe, 2002). Finally, a growing and broad area of application for spatial memory research derives from technological advances in the computer sciences that pose human factors engineering problems related to how devices may best utilize spatial interfaces. Wide-ranging areas such as the use of interactive tabletop computer displays (Kim & Maher, 2008), navigation within programs (Guerlain, 2007), and the military use of VE training simulators (Templeman & Sibert, 2007) all depend heavily upon an understanding of human spatial cognition and memory.

HISTORICAL LANDMARKS

From response learning to cognitive maps

Edward C. Tolman is recognized as the father of modern spatial memory research. His research program centered on the question of whether organisms navigate using stimulus–response associative mechanisms, as posited by the behaviorists of the day, or whether they use map-like spatial representations that describe relationships among features of the environment, a view that Tolman championed. Numerous studies conducted in this vein have indicated that organisms extract a rich representation of the spatial relationships in the environment that can be efficiently and effectively transformed when necessary (Olton, 1978; Tolman, 1948). This cognitive map framework provided an explanation of how complex spatial relationships may be stored in memory. It appears in the literature under numerous guises, sometimes called schema representations or survey knowledge (Taylor & Tversky, 1992). Tolman and subsequent researchers have shown how cognitive maps can be used by both humans and nonhuman animals to produce flexible and adaptive behaviors within complex spatial environments. A key question for future research is how modern technological tools may alter, enhance, or detract from the cognitive spatial maps people form.

Recognition of modality specific memory

Despite the early advances of Tolman's ideas for cognitive maps, cognitive psychologists of the 1960s tended to posit amodal representations of memory. However, research in the 1970s led to a general acceptance of modality specific memory stores. An important advancement to the understanding of spatial abilities arose from the introduction of the working memory model (Baddeley & Hitch, 1974), which proposed two independent rehearsal spaces, the phonological loop for auditory verbal information and the visuospatial sketchpad for visual and spatial information. Contemporary researchers take it as a given that there are specific working memory resources dedicated to manipulation and temporary storage of visuospatial information. Importantly, AR technologies may change the working memory demands of spatial memory processing, as linked information can be visualized directly rather than having to be retrieved from long-term applied to spatial representations. Shepard and Metzler (1971) demonstrated in a seminal study that people were able to mentally rotate objects. Mental rotation abilities are important from an applied perspective, with research focusing on surgical training (Peters & Battista, 2008) and video game expertise (Spence & Feng, 2010). Along similar lines of inquiry, Kosslyn and colleagues conducted several seminal studies of mental scanning and zooming that implied that the mind treats remembered images in a similar analog fashion to how it perceives the corresponding visual stimuli (Kosslyn, Ball, & Reiser, 1978). While this research placed short-term and long-term analog spatial memory representations on a firm footing, it was not without its critics. Pylyshyn (1973) argued that these "analog" demonstrations did not rule out an explanation in terms of an underlying propositional representation of spatial information. Within the propositional framework, spatial representations can be described in an amodal form with relational operators that code relevant spatial information, such as "on top of," "to the right of," or "close to." Although neuroimaging data provide further evidence of the existence of modality specific visuospatial representations in the brain (Farah, 1984; Kosslyn, Ganis, & Thompson, 2001), it is also clear that propositional or categorical encoding of spatial information is an important component of spatial memory.

Exploring the neural circuitry of spatial memory

In their seminal book, *The Hippocampus as a Cognitive Map*, O'Keefe and Nadel (1978) focused on the hippocampus as a key neural structure responsible for spatial memory processing. Their research is credited with the discovery of place cells, which are active whenever an organism is in a specific loca-

(2004) using the now standard Morris water maze, which requires that the animal use a metric coordinate system to encode location. Rats with hippocampal lesions showed large deficits in navigation to platforms hidden under the surface of the water as compared with controls, implying that critical place information was blocked by the lesions.

Further support for the key role of the hippocampus in spatial navigation comes from research on taxi drivers, whose right posterior hippocampus contained more gray matter volume than controls (Maguire et al., 2000; Maguire, Woollett, & Spiers, 2006). However, research from lesion studies in humans and nonhuman animals has demonstrated a more complex picture regarding the hippocampus and spatial memory. Spatial memories can sometimes be maintained in the face of large hippocampal lesions, and neural damage that does not include parahippocampal cortex typically does not impair spatial memory for long familiar environments (Moscovitch, Nadel, Winocur, Gilboa, & Rosenbaum, 2006). Furthermore, former taxi drivers with hippocampal damage due to Alzheimer's disease still showed knowledge for spatial locations they knew before the onset of the disease (Rosenbaum, Gao, Richards, Black, & Moscovitch, 2005). These findings suggest a broader spatial memory network, with the hippocampus needed to bind information across network components.

In line with this idea, parietal and frontal cortices have also been found to be linked to spatial memory. Recent studies using functional magnetic resonance imaging and transcranial magnetic stimulation in humans have also allowed researchers to investigate the role of the parietal cortex in spatial cognition and have demonstrated it to be an essential component for comprehending where objects are within the visual field (Sack, 2009). Furthermore, the frontal cortex may play a critical role in the processing of spatial memories through its relationship to working memory representation and processing (Kessels, Postma, Wijnalda, & de Haan, 2000). There is also clear evidence of a specialized parahippocampal place area that plays a critical role in scene recognition, and is activated when viewing large-scale places, such as cityscapes, as well as small-scale places, such as rooms (Epstein, Harris, Stanley, & Kanwisher, 1998).

SPHERES OF INQUIRY

The nature of spatial representations

Tolman's (1948) seminal research established cognitive spatial maps as a fundamental representation of spatial information in both humans and nonhuman animals. Pursuing this approach, Downs and Stea (1973) examined the steps involved in acquiring and using cognitive maps. First, the perceiver *acquires* information about the general layout of the environment through perception. This layout is *encoded* as a cognitive map (i.e., a set of interrelated locations that include distance and direction information) and *stored* in long-term memory. Later, when it is *recalled*, the cognitive map must be *decoded* in order to use necessary relational properties between geographic entities within the environment.

Lynch (1960) postulated that people remember the layout of cities through five environmental features: paths, edges, districts, nodes, and landmarks. Because people use paths to navigate, their representation of the environment is typically path bound. The egocentric perspective of navigation paths provides a great deal of information about the size of environmental features. In studying differences between acquiring information through maps and navigation, Thorndyke and Hayes-Roth (1982) proposed that map learning results in survey knowledge, an allocentric representation that provides access to the relationships among environmental features as a unitary whole. In contrast, learning through navigation results in route knowledge, an egocentric view that relies on knowing a sequence of behaviors when encountering the environmental features. When asked to transform learned spatial layouts into the opposite perspective, people show increased errors, supporting the general conclusion that spatial memory performance is decremented when one must transform the representation encoded in memory. One implication of this line of research is that while the structure of an environment may contribute to people getting lost, another large factor stems from developing incomplete cognitive maps or use of incorrect spatial strategies during navigation (Carlson, Hölscher, Shipley, & Dalton, 2010).

Memory for spatial information is also affected by retrieval factors. Montello, Richardson, Hegarty, and Provenza (1999) asked participants who learned locations through direct experience to either point to those locations or turn their bodies toward those locations. Even though the method of acquisition was the same in both conditions, participants who were asked to use a pointing device to indicate direction to the location showed higher error rates than those who were asked to turn their bodies. These results support the conclusion that the representation of spatial layout can change given the demands of the task at retrieval. Future research needs to address how the use of GPS devices and AR technology in navigation affects spatial memories. Will these be enhanced or decremented by the ease of navigation and the ready access to information?

Typically, maps can be considered allocentric or viewpoint independent, showing the interrelationships of the different elements in the environment as a configuration. But of course, the environment is typically encountered from an egocentric or viewer-based perspective. When facing a landmark, one must determine which way to turn. To utilize the cognitive map, one must match one's orientation toward landmarks to a given egocentrically encountered information into a form that allows it to be integrated with the allocentric internal map. The interplay between egocentric and allocentric representations has been well studied in recent years (Mou, McNamara, Rump, & Xiao, 2006; Shelton & McNamara, 1997; Waller, 2006). From this research, it is clear that under the right circumstances, both egocentric and allocentric representations of space are encoded during learning of the environmental layout. People prefer to make judgments about views that they have directly experienced, but when asked about a novel view, they can generate the imagined view required to solve the task. As new technologies such as virtual environments and augmented reality become more accessible to researchers, studies will clarify the role of these technologies in the use of and preference for different representations in spatial tasks.

While researchers have generally emphasized the cognitive map-like perceptual representation of space in memory, there is evidence that response-based representations are also used to encode memory. When rats are not trained from different orientations in the Morris water maze, they show response based errors in their swimming behavior (Brandeis, Brandys, & Yehuda, 1989). However, when learning the locations from different orientations, the rat quickly learns to swim relative to distal cues rather than follow a predominant motoric response. Developmental perspectives suggest that spatial layouts are first learned in the form of route knowledge, reflecting directions relative to landmarks along the way, and only through extensive experience does one develop the survey knowledge characteristic of cognitive spatial maps (Siegel & White, 1975).

In addition to encoding cognitive maps and associative sequences, propositional and categorical codes are also available and are presumably widely used. When trying to locate one's keys, it seems most reasondown on the counter by the stove. Kitchen, counter, and stove are all categorical markers that allow us to navigate through the spatial memory of the larger environment (i.e., house) quite efficiently. These types of categories and relational properties, such as "left of" and "below," are critical verbal descriptions that allow us to localize objects. As discussed later, the categorization process can often lead to a distortion of the remembered location for an object. As a simple example of types of potential errors, consider which is further west, Reno or San Diego? Most people would incorrectly indicate that San Diego is further west, as San Diego is in California, which is west of Nevada, the state in which Reno is located (Stevens & Coupe, 1978). Thus, categorical memory, while robust and accessible, can sometimes lead to inferring erroneous spatial relationships. Studies of the interplay between spatial memory and language have produced a rich body of research literature that indicates a strong influence of verbalization on spatial representation in memory (Noordzij & Postma, 2005; Rinck, 2005; Zwaan & Radvansky, 1998). An unexplored area of research is the effect of augmented reality and GPS on the use of verbal characteristics of space. Will people's ability to describe where one landmark is in relation to another improve if they have access to portable interactive mapping technology?

Distortions of spatial memory

We have considered the various ways spatial information may be represented in memory. When using spatial memory, presumably different types of representations may be retrieved and acted upon. As with many cognitive tasks, the errors observed in spatial memory tasks can be very informative in revealing the processes and representations being used. In this section we focus on research that has attempted to explain the basis for the many systematic distortions observed in spatial memory tasks.

Schema based distortions

Tversky (1993) proposed two explanations for frequent errors found in spatial memory studies. First, she noted that cognitive maps are not rigid templates for environmental layouts, but rather they are more like a cognitive collage. People learn small pieces of environments very well. When spending time in one particular location, one experiences the relative positions of objects within the environment from specific egocentric viewpoints. When one navigates to different locations, one learns the relative positions of objects in that environment. What happens when one is subsequently asked to make judgments of location across these two districts? Presumably, one must quickly create a larger cognitive map from the previously existing smaller cognitive maps. The resulting constructed map will naturally have areas of high fidelity and low fidelity. This constructive view of cognitive mapping then argues that errors in spatial memory occur because the new representation is like a patchwork quilt rather than a seamless, accurate map.

Tversky (1993) also noted that errors occur when mentally representing well known environments. She argued that these result from the use of schemas or *spatial mental models*, which store expectations about position, orientation, and size of features. These learned expectations then lead to the use of heuristics that enhance efficiency in responding to the required task but may distort memories for spatial layouts. Use of spatial mental models often leads to regularizing the configuration, such as aligning the configuration with cardinal directions, smoothing out irregular boundaries, etc.

Taylor and Tversky (1992) further discuss how people tend to rely on hierarchical grouping of landmarks to help them organize environmental features. For example, they may think of the mountains, trees, and rivers as being natural features and will remember those locations as a group configuration. Similar clustering will occur with buildings, streets, and other manmade landmarks. These clustering rules are derived in part from gestalt principles of organization. More generally, the idea that people use spatial mental models to organize spatial information in memory is consistent with the proposition of other researchers that spatial information is encoded at two levels, coarse and fine-grain, and that the coarse, categorical representation leads to systematic distortions in memory.

Location memory

A particularly productive way to consider distortions of spatial memory locations is within the framework of the category-adjustment model developed by Huttenlocher and colleagues (Huttenlocher, Hedges, & Duncan, 1991). The category-adjustment model assumes that locations are encoded at the level of fine-grain memory, reflecting angular and metric properties of the representation, and at the level of categorical memory, reflecting a grosser partitioning of the space. Spatial categories can be represented by boundaries, such as the wall between the kitchen and the living room, and also by prototypes, corresponding for example to the central tendency of the category (i.e., the center of the kitchen). These fine-grain and categorical memory representations differ not only in their level of detail, but also in how robust and accessible the memories are. Although highly accurate, fine-grain memory is posited to be fragile and forgotten quickly. The coarser categorical memory, by contrast, is highly robust and accessible. The category-adjustment model posits that the individual attempts to recall locations through retrieval of the fine-grain memory representation. However, to the degree that the fine-grain memory is uncertain, the remembered location is shifted toward the corresponding category prototype. Accordingly, research has demonstrated that forgetting induced by delays or interference tasks results in estimates that are more dependent on categorical encoding and hence reflect greater bias toward category prototypes (Fitting, Wedell, & Allen, 2007b; Hund & Plumert, 2002; Huttenlocher et al., 1991). Although the influence of category prototypes results in systematic bias in recall, it reduces overall memory error and is thereby considered to reflect adaptive behavior.

Researchers have begun to tease apart whether these effects occur at encoding or retrieval stages of processing. Research by Sargent, Dopkins, and Philbeck (2011) is supportive of the idea that spatial categories can be reorganized at retrieval. The pattern of angular bias they found implied that rotating the participant's egocentric orientation to the task field led to the establishment of new spatial categories centered on the new heading. Sampaio and Wang (2009) found strong evidence supporting a retrieval basis for category bias, such that reproduced locations showed the usual bias toward the prototype but recognition tests of location did not. The issue of whether category influences are formed when first encountering the environment or are determined by the current context has implications for the use of GPS, AR, and VEs. Hutcheson and Wedell (2012), in a VE task, found differences in the bias when remembering locations from an egocentric or allocentric viewpoint, implying that the viewpoint presented by the VE is a strong determinant of the nature of the bias. These effects may be important when applied to VE applications of flying planes or locating mines or persons.

Distance memory

Memory biases also apply to judgments of components of spatial location, such as remembered distances and angles. As discussed by Montello (1997) many factors can affect distance estimates. Measurement techniques can lead to specific bias patterns. Having participants draw maps forces them to think about the overall layout of the environment rather than just a single distance between two points, and may lead to regularization of distances (Tversky, 1993). Requiring participants to give verbal or physical estimates of distance with a learned metric may be problematic as it provides only relative rather than absolute accuracy. Other researchers have had participants reproduce the distance between two points in a nonsymbolic way, such as experiencing a blindfolded walk between two marks on the floor and then being asked to walk back to the first mark. This technique works well only for a small number of estimations. Methods for maximizing accuracy of recall distances have practical implications for eyewitness testimony, in which remembered distances may be important determinants of who is at fault. Research shows that people not only recognize events more poorly as distance increases but that they are also inaccurate in remembering the distance to the event itself (Lindsay, Semmler, Weber, Brewer, & Lindsay, 2008).

Environmental and situational factors may affect distance memory. Increasing the time it takes to travel the distance or the effort required to reach a destination often results in an overestimation of distance (Montello, 1997). Multiple studies have found that partitions across spatial categories can have a large influence on estimated distance. People remember distances that cross spatial regions as greater than like distances within a spatial region (Allen & Kirasic, 1985; Sadalla, Staplin, & Burroughs, 1979). The number of turns one takes along a path can be a powerful influence on the perception and memory of distance. The route angularity effect, as it has become known, is the finding that the more turns a person encounters along a path, the longer the person remembers the path to be. This effect can be present in both real and virtual environments used to test spatial abilities (Jansen-Osmann & Berendt, 2002; Sadalla & Magel, 1980). Hutcheson and Wedell (2009) demonstrated in a VE how the route angularity effect is consistent with using number of turns as a heuristic to estimating distance when fine-grain memory for the traveled path is disrupted by either a concurrent task at encoding or a filled delay after traversing the route. These results help to explain why the route angularity effect is not observed when the memory demands of the task are low.

Angle memory

Angular estimates are frequently used to assess spatial memory, as when blindfolded participants are asked to point to locations in an array they have memorized, or when one is asked to point in the direction of as unseen specific location after navigating different paths (Waller, Knapp, & Hunt, 2001). Memory for angles may also be applied to surfaces encountered in an environment (angles of inclination and declination) along with direction in the horizontal plane (azimuth).

An important issue reflecting measurement of angles in memory is whether these are expressed directly through motor movements or must be translated into a verbal expression, such as a measure of degrees. Creem and Profitt (1998) found that when participants made responses within a few seconds of viewing, motor estimates of inclination were very accurate but verbal estimates were strongly biased upward. They interpreted these results as reflecting two memory systems. The motor system briefly stores information for guiding actions and functions within an egocentric frame that provides rapid and precise responding. The verbal system is based on explicit memory, requires effortful computation, is flexible and long lasting but is subject to biases.

While there is good evidence supporting the distinction between motor and verbal response systems in many perceptual tasks, research by Haun, Allen, and Wedell (2005) suggests that the systems may not be as distinct as first posited by Creem and Proffitt (1998). Using a wider range of inclination angles and also measuring azimuth, their results were consistent with previous results in that motor estimates were more accurate and less biased than verbal estimates. However, inconsistent with the idea of two completely separate systems, they found significant bias for motor estimates that was of the same pattern as found for verbal estimates and consistent with Huttenlocher et al.'s (1991) category-adjustment model.

Research also suggests that estimation of angles in real world settings may depend on contextual factors. Estimates of steepness of hills are influenced by the presence of a friend (Schnall, Harber, Stefanucci, & Proffitt, 2008), and also by glucose intake (Schnall, Zadra, & Proffitt, 2010). What might the effects of VE depictions and AR information be on memory for steepness of the terrain we encounter?

Verbal descriptions of space

A final area of consideration for understanding distortions of spatial memory is the role of verbal descriptions. People are quite sensitive to the various kinds of statements made when describing a route that would allow them to reach a desired location. They need to know the temporal/spatial order of landmarks and how to respond to those landmarks while avoiding confusion during the description to maintain mutual knowledge (Allen, 2000). Ferguson and Hegarty (1994) found that the type of landmarks provided in a written description of space to a person can change the accuracy for recalling spatial layout. Their study shows that important "anchor" landmarks are used to maintain spatial memories for environmental layout regardless of whether the description is written in route or survey terminology, whether or not they were given a map, whether the anchor landmarks were described first, or the level of detail provided. Thus some features of spatial memory generated from verbal descriptions appear more malleable than others.

Once again eyewitness testimony may be an important area to explore how verbal reports influence memory for spatial layouts. Research on the verbal overshadowing effect finds that verbal reports may degrade later retrieval of memories for experienced stimuli (Meissner, Brigham, & Kelley, 2001). This may provide researchers with a firm basis for explaining real world errors in spatial memory for learned locations. Additionally, AR applications are an important arena for exploring the interface of verbal and spatial descriptions of layouts.

Dynamic spatial memory

As we gain experience in an environment, our spatial memories may change to incorporate new information. Wayfinding, or the process of mentally and physically navigating toward a desired location, is particularly relevant to understanding applications of spatial memory, as this is a key applied task. According to Siegel and White's (1975) research on wayfinding, a person acquires route knowledge by learning a sequence of turns at specific landmarks. Over time, the person begins to form a more map-like representation of the environment, referred to as survey knowledge. This type of representation is more flexible than route knowledge, as it is less reliant on proximal landmarks and may use distal cues, such as celestial bodies or large faraway buildings, to maintain a sense of heading. In some environments, one may need to maintain a sense of distance and direction traveled even if one cannot see relevant environmental cues, a process referred to as spatial updating. For example, when the power goes out at home, one may find oneself in total darkness and have to locate another light source without visual cues. Remembering that there are candles in the kitchen, one can get up off of the couch and slowly move to where one believes the kitchen door is located. This action may start with an initial heading based on the angular assessment of starting point and destination point. As travel proceeds, one must be careful to determine distance traveled to avoid bumping into obstacles. At any given point, course adjustments may be needed along with consideration of the relative location of objects in the environment. People's ability to carry out these types of tasks suggests that spatial updating is robust and possibly automated.

A common way to test spatial updating is to blindfold participants and have them perform a triangle completion task, as illustrated in Figure 5.1. From the starting position, experimenters guide participants forward, then through a turn and another forward leg of the triangle. At this point participants are asked to turn and walk back to the starting position on their own while still blindfolded. As shown in Figure 5.1, three measures of performance are typically obtained: angular error, distance error, and absolute error. To successfully complete this task requires that the participant maintains a sense of distance and direction traveled by understanding how much muscular exertion has been required (kinesthetic cues) and how much motion has been perceived using the movement of fluid in the ears' semicircular canals (vestibular cues). Studies using this method have found that participants with sight tend to have more difficulty with this task than congenitally blind participants. While people generally can get close to the targeted destination using only kinesthetic and vestibular cues, sighted individuals use visual cues to correct for errors as they update their location (Klatzky, Loomis, Beall, Chance, & Golledge, 1998).

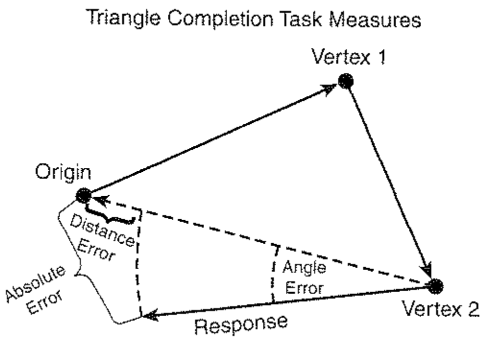

Figure 5.1 Illustration of the triangle completion task and related measures. The blindfolded participant starts at the origin and is guided to the first vertex, turned, and guided to the second vertex. At this point, participants must turn and walk to where they believe they started. The absolute error is the distance from the origin to where participants stopped. This can be decomposed into angle error and distance error.

Two basic processes have been posited to explain how updating is accomplished. One account assumes that spatial updating is a continuous cognitive act that occurs during navigation and that requires spatial working memory resources (Sholl & Fraone, 2004; Wang et al., 2006). The second assumes that spatial updating occurs after navigation is completed and a location is prompted, referred to as offline updating (Hodgson & Waller, 2006). Although both of these accounts predict the requirement of cognitive resources, they make different predictions about the time course for using those resources. There currently is support for both of these spatial updating processes, depending on task constraints. Allen, Kirasic, Rashotte, and Haun (2004) compared updating in younger and older adults using a triangle completion task in which participants either walked the paths (kinesthetic and vestibular cues) or rode a wheel chair through the paths (vestibular cues only). The results indicate that kinesthetic-based updating is more robust across aging than vestibular-based updating, with working memory measures significantly predicting nearly all the age related variance in signed direction and distance errors. Thus, cognitive resources appear to be needed for updating when environmental feedback is held at a minimum.

Both wayfinding and spatial updating often require people to change orientation to their cognitive maps in order to find their target location. Even when an environment feature is learned from a fixed orientation, a person may need to locate it from a different orientation. Research in this area demonstrates that when asked about the location of a landmark from a rotated perspective, people can do this as well, but performance is often resource dependent (Presson, DeLange, & Hazelrigg, 1989; Sholl & Nolin, 1997). Future research should investigate the impact of the use of advanced technologies on this resource intensive perspective taking task. Will use of VEs and GPS help or hurt abilities to reorient to the environment? Will unburdening working memory resources through the use of AR provide the needed resources to aid in this task?

Finally, we note how the category-adjustment model described earlier can relate to navigation. Fitting, Wedell, and Allen (2009) studied how participants navigated a rat icon though a simulated Morris water maze to find a hidden platform while varying the number and location of cues. They found clear evidence that participants formed cue-based categories to guide their navigation toward the remembered locations, as indicated by heading error bias and bias near the end of the path. In another study, Fitting et al., (2007a) had participants remember locations in a 3 m arena and also found cue-based bias. These studies suggest that at least in these sparse environments, cues may be used to create spatial categories and that navigation tends to proceed toward the center of the spatial category in which the location is situated. However, in a recent study, Hutcheson and Wedell (2012) found that size of the environment may matter. When participants had to remember locations encoded via a map view by navigating to them within a large scale VE, manipulation of distal cue placement once again resulted in bias patterns that indicated cue-based categories. However, unlike the smaller scale results, cues did not correspond to category prototypes but rather to category boundaries. Thus, when cues are distal and viewed using an egocentric orientation within a large space, they may function primarily to orient one to the space and hence form natural boundaries or category partitions.

Individual differences

Sex differences in spatial abilities have been widely studied for decades. The finding that males tend to outperform females in mental self-report measures to get a sense of the strategies used in wayfinding, women tend to use route knowledge more than men, especially as familiarity with the environment increased. Men tend to show less spatial anxiety, better sense of direction, and greater willingness to try shortcuts, suggestive of more complete cognitive maps (Lawton, 2001; Prestopnik & Roskos-Ewoldsen, 2000). Explanations for these differences often center on hormonal influences (Silverman & Phillips, 1993) or enhancement of abilities through specialized training such as video game play (Spence & Feng, 2010), which is more common in males.

Occupations and activities that may promote individual differences in spatial abilities need to be further documented in the literature. Individuals who use American Sign Language tend to be better at mental imagery than those who do not (Emmorey & Kosslyn, 1996). More recently there has been a spate of research investigating how video gamers may enhance spatial abilities through brain related changes (Spence & Feng, 2010). From the research on expertise, it is clear that experts in a domain have access to better schemas for problem solving than novices, who focus on the physical properties of the stimulus rather than the underlying principles of the problem (Glaser, 1984). Likewise, researchers who study location memory should strive to understand the effects associated with jobs that require the use of spatial representations, such as architecture, engineering, and product design. A better understanding of how expertise affects spatial memory is needed, with an emphasis on mechanisms through which this is achieved.

CONCLUSION

As we move into an age in which complex navigational devices are small enough to general public has access to technology only considered in science fiction a few decades ago. This increased instant access to a wide array of spatial information may have both detrimental and beneficial consequences. Increased reliance on navigation tools may lead to poorer overall spatial memory, as less attention is paid to where one is going and what are the relevant landmarks. On the other hand, well designed information enhancement can lead to more efficient navigation and free up working memory resources that aid in spatial memory integration. Future research is critical to understanding how human spatial memory will function in this new information era.

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