Animal Spatial Cognition:

Comparative, Neural & Computational Approaches

Edited and Published by

Michael F. Brown
Department of Psychology
Villanova University

and

Robert G. Cook
Department of Psychology
Tufts University

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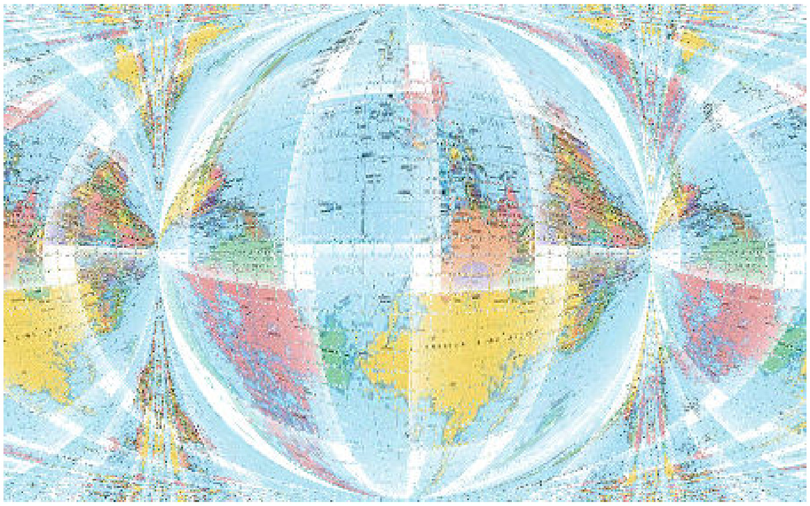

Updating Human Spatial Memory

Holly A. Taylor & David N. Rapp
Tufts University & Northwestern University

Abstract

Humans have developed different ways to represent spatial information, both in memory and in off-line formats, such as maps and spatial descriptions. These representational systems have developed to deal with environment complexity, the many goals one might have within an environment, and the changes that occur both within the environment and pertaining to how it is used. The present chapter discusses ways in which we build and update spatial representations based on (1) direct experiences (e.g., navigating an environment) and (2) more symbolic experiences. The focus in comparing different acquisition sources is to elucidate the many stimuli-driven, goal-driven, and participant-driven factors that affect spatial processing, and in so doing extract some general cognitive mechanisms underlying human development and use of *cognitive maps*.

Chapter Outline & Navigation

I. Introduction

Driving successfully through the streets of Boston can be an enormous challenge. This challenge is less a function of the other drivers, who at times may be aggressive and creative in road rule interpretation, but rather is mainly due to the complexity of the environment. Traffic rotaries, one-way streets, and road configurations that rarely align with grid-like patterns can create navigation nightmares (see Figure 1). This notion is not lost on the local populace: Urban legend purports a city rotary designed only with one-way streets feeding into the rotary. Even recent attempts to alleviate traffic difficulties have created further challenges. Consider the infamous Big Dig, a major ongoing construction project designed to revamp both above- and below-ground traffic routes through the city, alleviating traffic snarls through the heart of Boston. Work on the Big Dig frequently creates extended detours through the already existing maze of streets and thoroughfares. These detours add to the challenge of navigating these complex neighborhood thoroughfares since they force drivers to update their mental representation of the city to accommodate uncertain changes. Since a detour can be experienced at virtually any point along one's normal route, accessing and updating one's mental representation must be done out of some previously learned sequence. Such experiences are not limited to those involving Boston (although some Bostonians might take issue with that notion); consider the last time you negotiated your way around a construction detour or traffic jam, guessed where to go next given an underspecified set of directions, or tried to find your way in your favorite city after being away for a long period of time (and finding much has changed). How do we update our memories of space to successfully navigate through varying, complex, and sometimes changing environments?

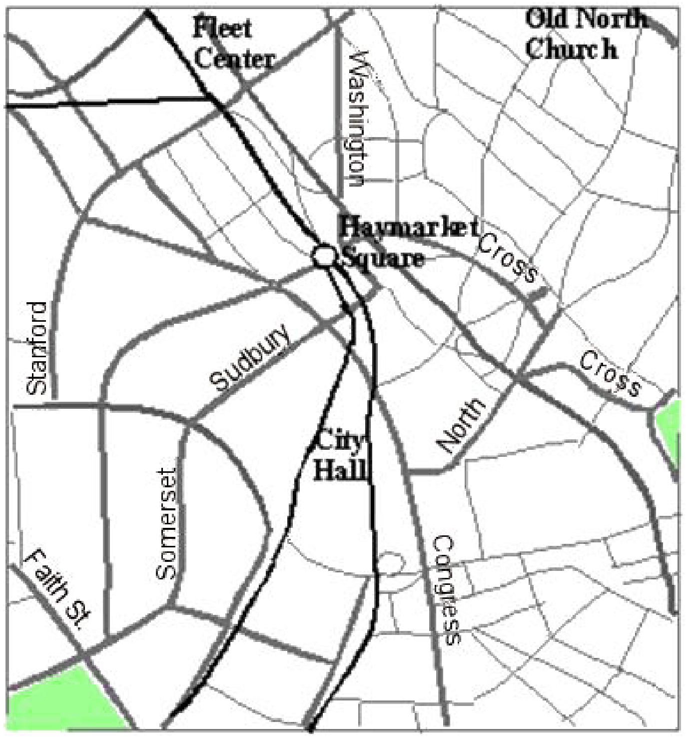

Figure 1. A schematic map showing the road complexity of downtown Boston.

Some of the earliest, preliminary work on updating spatial representations comes from Tolman's (1948) research on how animals mentally represent environments (Tolman, 1948; Tolman & Honzik, 1930). In these studies, rats learned to navigate a maze and, with sufficient training, could generate novel shortcuts through the environment. Tolman described these mental representations or memories as *cognitive maps*. While the nature and definition of such mental representations remains a matter of debate (for definitional and interpretive discussion see Bennett, 1996), rats' use of novel shortcuts suggests that the environment was represented in a form that could be accessed "out of sequence"; that is, in ways beyond that which had been learned. In other words, animals can use their mental representations of environments to do more than follow a well-worn path. Some believe that human navigators demonstrate even greater flexibility than animals like rats in their ability to access information "out of sequence" from their cognitive maps (e.g., Taylor, Naylor, & Chechile, 1999; Taylor & Tversky, 1992b). This flexibility includes the mental manipulation of spatial information based on different orientations, perspectives, and geographic scales, from a wide variety of acquisition sources (maps, navigation, and spoken or written language).(See Schmajuk & Voicu, this volume.)

While early work on spatial representations relied on non-human experimentation, current examinations of spatial cognition involve investigations of both human and non-human species. Can we derive general principles from such work? Indeed some human spatial processing is achieved through neural circuitry shared with non-human animal species, particularly the hippocampus (e.g., McNamara & Shelton, 2003; e.g., O'Keefe & Nadel, 1978; Wang & Spelke, 2002; also see Mizumori & Smith, this volume). Beyond these structural similarities there are, perhaps not surprisingly, some functional similarities between humans and non-humans' use of a cognitive map (e.g., O'Keefe & Nadel, 1978). For example, both humans and non-humans sometimes use an environment's shape to guide navigation (Gallistel, 1990; Gouteux & Spelke, 2001; Hermer & Spelke, 1994). Even more compelling, and for some individuals quite controversial, is the idea that there may be similar underlying processes or activities involved in constructing and accessing human and non-human spatial representations. (For a discussion of this issue see Wang & Spelke, 2002.)

There are also important differences between human and non-human animals' spatial representations. Perhaps most importantly, humans, unlike non-humans, have evolved mechanisms to represent spatial information symbolically (Gattis, 2001; Gauvain, 2001; Glasgow, Narayanan, & Chandrasekaran, 1995; Plumert, Ewert, & Spear, 1995; Taylor & Tversky, 1992a; Uttal, 2000). These representational mechanisms allow humans to acquire spatial information from means other than through direct experience. Indeed, humans gather a substantial amount of spatial information from symbolically mediated sources, such as maps, diagrams, and verbal descriptions. Importantly, cognitive maps constructed from such indirect, symbolic sources have been shown to differ from those derived from direct, navigational experience in some ways (e.g., Thorndyke & Hayes-Roth, 1982) and yet similar in other ways (e.g., Taylor et al., 1999).

The evolutionary mechanisms in humans that allow for symbolic spatial representations may also allow for ready flexibility in thinking about and using spatial information beyond the activities exhibited by non-human animals. By flexibility, we mean the ability to use spatial information in novel ways that transcend direct experience, including updating and manipulation. The short-cuts shown by Tolman's (1948) rats certainly transcend direct experience to a degree. However, this flexibility is extended in humans with symbolic representations, as the activities involved in building such representations bear little surface resemblance to the direct experience of navigating through an environment. A map uses visual and verbal symbols, often to depict an environment that is more vast and complex than what can be experienced from a single vantage point. Maps give direct information about spatial relationships between locations, but rarely provide spatial information relative to the individual and generally take a perspective above rather than within the environment (MacEachren, 1994, 1995). Verbal or text-based spatial descriptions can rely solely on language; thus many spatial relations are not explicitly provided in the linguistic stimuli and must be inferred. These descriptions may take either a within-environment (route) or above-environment (survey) perspective and generally omit metric detail to increase comprehensibility (Taylor & Tversky, 1992b). Yet, humans demonstrate a facile ability to construct cognitive maps from both cartographic maps and spatial descriptions (Taylor & Tversky, 1992a, 1992b, 1996; Thorndyke & Hayes-Roth, 1982).

Even the concept of a cognitive map implies flexibility in thinking about spatial information since a *map*, whether it be physical or mental, takes a different perspective on an environment than does actual navigation (the most common form of direct experience). Of course, there are numerous ways in which humans interact with spatial environments and numerous ways in which environments relate to one another and can be integrated. These factors can combine to create a variety of situations for humans to experience spatial information, indeed more than one could hope to comprehensively count.

In this chapter, we will examine evidence on updating and manipulating spatial representations across some of these situations, drawing conclusions about general cognitive mechanisms that are involved with some types of spatial mental representation use. In particular, we will concentrate our discussion on the ways in which we build and update spatial representations based on (1) direct experiences (e.g., navigating an environment) and (2) more symbolic experiences (e.g., studying a map of an environment or reading a spatial description), with a particular focus on situations that require using spatial information "out of sequence." Our ability to comprehend this latter, symbolic form of experience in a wide variety of contexts may be what distinguishes us from non-human animals. Within the human animal, though, many of the processes and products of spatial cognition may be invariant across symbolic and direct experiences in human information processing.

II. Updating Representations

2.1 Across Orientations

As we have just described, one method for acquiring spatial representations involves direct experience navigating an environment. Representations based on navigation have been suggested to be orientation-free, meaning that information can be accessed from the representation equally well from any orientation (e.g., Sholl, 1987). In any navigation experience, one experiences the environment from many different orientations and vantage points. Every turn results in a new orientation; every step results in a new vantage point. The idea of an orientation-free mental representation comes from the need to integrate experiences based on multiple views acquired during navigation. Only through integration can one more fully represent the whole environment, particularly environments that cannot be experienced from a single orientation (e.g., a building, a college campus, or a town). Thus, an important issue is how a spatial representation is constructed or built from these individual "snapshot" views of space. While the idea of orientation-free representations from navigation may make intuitive sense, empirical evidence has not always concurred with those intuitions.

For example, what happens when an environment is experienced from more than one, but still a limited number, of orientations? Shelton and McNamara (1997) had participants learn an object array from two views, with the goal of determining whether multiple views would facilitate the construction of an orientation-free representation. Contrary to the orientation-free idea, their results suggested that people maintained two orientation-dependent representations - one for each studied view. In other words, their participants' representations were more like mental snapshots. Furthermore, Diwadkar and McNamara (1997) showed that when tested on novel views, participants needed to reconcile the novel view with the studied view, which led to cognitive difficulty as indicated by response time differences.

Yet while performance appears orientation-dependent with multiple, limited views, the underlying mental representation does not seem necessarily tied to actual viewing orientations. Mou and McNamara (2002) had participants attend to an intrinsic axis within an object layout. The intrinsic axis is one internal to the array and in this case was created through the alignment of objects within the array. The intrinsic axis was either congruent with or displaced from the participants' actual viewing direction. Results showed an orientation-dependent representation tied to the intrinsic rather than the viewing axis. Pointing accuracy was actually greater when activities were aligned with the intrinsic axis, regardless of facing direction. Additionally, novel headings orthogonal to this axis led to more accurate pointing judgments than other headings. So, this study shows orientation-dependence rather than orientation-independence as a function of direct spatial experience

In further examinations of orientation-free representations, Shelton and McNamara (2001a) had participants learn a layout of objects from one, two, or three viewpoints. The viewpoints were either aligned (see Figure 2A) or not aligned with a salient, environment-defined reference frame (see Figure 2B), in this case the walls of the room. Results indicated that if a viewpoint aligned with the environment reference frame, other actual viewpoints were not as strongly represented. Imagine that David learned the object array in Figure 2A standing on the side of the mat between the phone and flower vase. Holly, in contrast, learned the object array in Figure 2B, standing on the side of the mat between the flower vase and the stack of books. The actual viewpoint experienced by Holly would not be represented as strongly as the one experienced by David because Holly's was not aligned with the walls of the room.

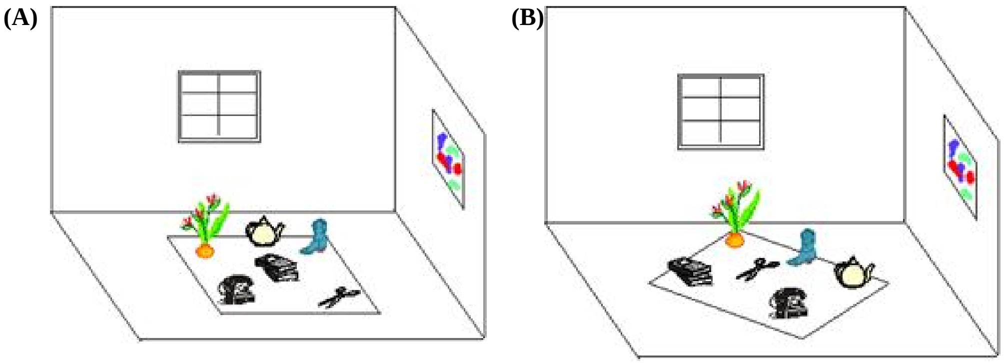

Figure 2. A spatial array based on Shelton and McNamara (2001a) wherein (A) local reference frame is aligned with the global reference frame defined by the room and wherein (B) local reference frame is misaligned with the global reference frame defined by the room.

In a cross-modal version of this task, Shelton and McNamara (2001b) had participants view a table-top object layout and then manually, without visual access, reconstruct it from either the same or a rotated orientation. They found better *visual* memory for the manually reconstructed viewpoint than for the visually experienced one. Taken together, these findings indicate that for object layouts experienced from several, but still a limited number of viewpoints, participants represent the layout in orientation-dependent ways. The fact that the orientation dependency is not necessarily tied to the viewing orientation suggests that humans possess the cognitive facility and flexibility to develop and update mental representations that differ from perceptual experience.

Our cognitive apparatus appears to take advantage of a variety of different reference frames (e.g., egocentric, intrinsic, or environmental), depending on availability in the environment, any of which could form the basis of orientation-dependency in a mental representation. It is important to note that in the studies just reviewed, the entire spatial array or environment could be viewed from a single vantage point.

Unlike a spatial array that can be viewed completely from a single vantage-point, many real-world environments, such as a college campus, cannot be completely experienced from a single viewpoint. How does the variety of viewpoint experiences we have with these environments impact the resultant mental representation? McNamara, Rump, and Werner (2003) investigated mental representations developed from navigation through a large-scale, real-world environment (the Parthenon and its surrounding park in Nashville, Tennessee). Participants navigated through the environment on a path that was either aligned or misaligned with the walls of the Parthenon. Participants in the aligned path condition used the structure of the Parthenon to guide their representations, showing increased pointing accuracy for heading directions aligned with the structure's walls. Those in the misaligned condition relied on an obvious landmark (a nearby lake) as a central reference point in their mental representation. This finding suggests that mental representations involve the use of reference frames as defined by the environment, but that are also influenced by our direct egocentric experience with that environment.

Navigation within an environment actually involves two types of changes - rotation and translation. A simple rotation would involve turning in place; a simple translation would involve walking forward. These two types of changes are obviously used in concert during navigation. Rotational or orientation changes seem more difficult to update than translation changes (Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989). The ability to update also appears tied to actual locomotion. Self-movement facilitates automatic updating of spatial relations (Farrell & Robertson, 1998). Rieser, Garing, and Young (1994) found that young children could imagine perspective changes when they were tied to physical actions, but not when they were only imagined. In contrast, adults could imagine perspective changes, but were slower to do so than when changes involved actual physical motion. Furthermore, errors in updating an imagined heading appear tied to perceptual representations of the body (Avraamides, Klatzky, Loomis, & Golledge, 2004) and error is reduced when body-based information is available (Waller, Loomis, & Haun, 2004).

Orientation-free representations based on navigation would seem to afford the most flexibility for updating "out of sequence." The intuition underlying the idea of orientation-free representations comes from the integration of many and varied experiences with an environment in terms of both orientation and vantage point, with changes in position taking place through both rotation and translation. Yet, as reviewed above, the empirical evidence has not provided consistent support for orientation-free representations. Sholl and Nolin (1997), based on five studies, suggest that orientation-free performance is only evidenced under a certain set of conditions and if any one of those conditions is not met, performance will be orientation-dependent. The conditions outlined include a horizontal viewing angle during encoding, a room-sized test space, and "on-path" testing. Some of these conditions suggest that spatial perspective plays a role in spatial representation use, particularly when considering how such representations are used "out of sequence."

2.2 Across Perspectives

When considering how people gather and use spatial information, particularly symbolic information sources, a shift in perspective is frequently involved. Navigation necessarily involves a within-environment or route perspective. This would map on to the horizontal viewing angle suggested by Sholl and Nolin (1997). As one moves in the environment, landmarks are viewed relative to one's current position in the environment. Spatial experiences other than direct navigation can differ with respect to perspective. For instance, spatial descriptions can also relate a route perspective while maps, in contrast, present a spatial perspective from above, also known as a survey perspective. Spatial descriptions can also adopt a survey perspective, or can even mix survey and route perspectives (Taylor & Tversky, 1996).

When using symbolic sources, shifts between route and survey perspectives are not uncommon. For example, someone may draw a map of an area they have only experienced through direct navigation, such as one provided in invitations to dinner party guests. The guests, in turn, must shift between spatial perspectives in the opposite direction by using the map to navigate to the party. That is, they use a survey perspective provided by the host to help configure a route perspective that will lead them from their home to the party. Although these perspective shifting tasks are commonplace, they are anything but cognitively simple.

To understand the cognitive activities involved in switching or updating across perspectives, one must understand the mental representations involved. Is a mental representation a function of the perspective learned? Based on the existing research, the answer is unclear. Some findings support different representations from maps and navigation (e.g., Thorndyke & Hayes-Roth, 1982). For example, Sholl (2000) argues that the coordinate systems used to access spatial information are separable and are derived from the learned perspective. Navigation uses a body-centered system and maps use an object-centered system. Thus, people would have different representations structured by the perspective learned. As discussed above, the differences may relate to having an orientation-free mental representation following navigation and an orientation-specific one following map study (Sholl, 1987). Opposing views suggest either no perspective-based differences in mental representations (McNamara, Hardy, &

Hirtle, 1989) or changes in mental representations only resulting from extensive experience with an environment (Golledge & Spector, 1978; Thorndyke & Hayes-Roth, 1982). This latter explanation has been embodied in computational models of spatial memory wherein iterative manipulation of route information leads to accurate survey perspective inferences and better updating "out of sequence" (Kuipers, 1978; Leiser & Zilbershatz, 1989).

Why do some studies find perspective-based differences and others do not? Several factors may account for these seemingly contradictory results, all of which have implications for how individuals use spatial models across perspectives. The representational strategy adopted may rely on situational factors, for example whether landmarks can be reliably recruited. Foo, Warren, Duchon, and Tarr (2005) found that participants relied on landmarks when available, but if landmarks appeared unreliable, they would switch to a rough, survey-based representation. In fact, they appeared unable to find novel paths through environments that were devoid of landmarks. Beyond map characteristics, individuals' goals for a spatial task can also influence the mental representation people construct and apply. Taylor, Naylor, and Chechile (1999) obtained representational differences depending on both how people learned an environment and what they expected to do with their knowledge. A survey-perspective goal led to better performance on survey-perspective tasks while a route-perspective goal led to better performance on route-perspective tasks. Additionally, the amount of experience an individual accumulates in an environment may influence spatial representations. People seem to develop mental representations with more survey perspective characteristics with longer exposure to the environment. Combining these various characteristics, Thorndyke and Hayes-Roth (1982) found perspective differences based on learning format, either map or navigation. Navigation learning led to an improved ability to orient to unseen locations and estimate route distances; map learning lead to superior judgments of relative location and straight-line distances. However, the map learning advantage disappeared for people with extensive navigation experience.

Taken together, these results indicate that cognitive flexibility for thinking about the same spatial information from different perspectives increases with increased experience, whether this experience is based on actual navigation or mentally derived from specific learning goals. The results also indicate that people can use, to their advantage, the information available in a variety of ways and "out of sequence." Landmarks may be ideal for navigating, but when absent, people appear to recruit and use the information that is available, even when this requires switching perspectives.

2.3 Across Scales

Real-world environments have nested units (see Schmajuk & Voicu, this volume). Rooms are positioned within buildings, buildings are located within towns, towns appear within counties, etc. (see Figure 3). While evidence suggests that people continuously update their spatial representations as they move (Wang & Spelke, 2000) through a process referred to as spatial updating (Wang & Brockmole, 2003a, 2003b), whether such updating simultaneously incorporates these various levels of nesting is not clear. Extant evidence suggests that it does not. Environmental objects appear to be egocentrically updated one by one as opposed to calculating one's position within the environment as a whole (Wang & Spelke, 2000). Thus, the representational system selects the most important objects or locations.

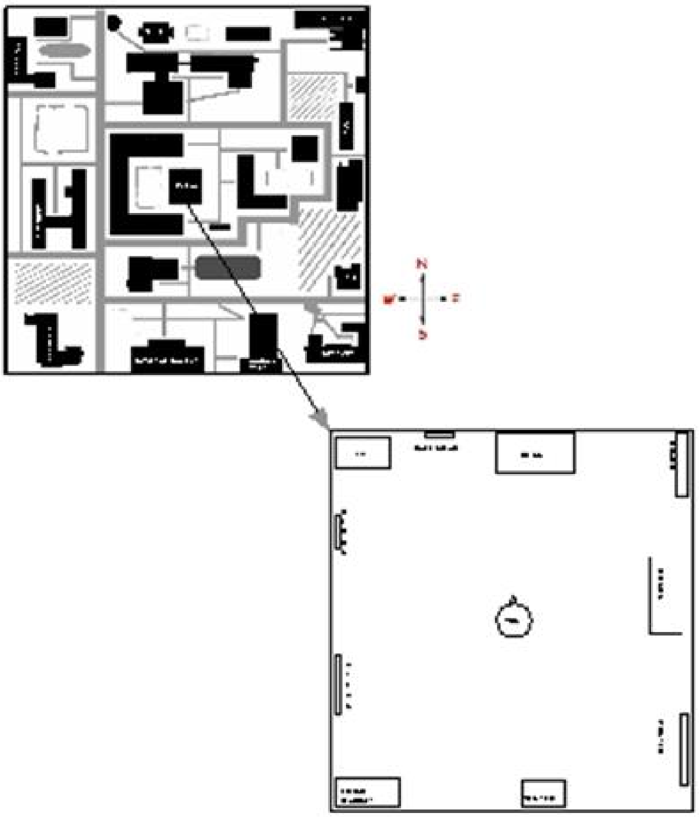

Figure 3. A map depicting environment nesting. Insert portion of map illustrates a room within building on this college campus (Bilge & Taylor, 2006).

Which objects may be selected as "most important"? From the point of view of navigation, objects in the immediate surround, which may be bumped into or tripped on, would seem important to track. Consistent with this, Wang and Brockmole (2003a) found automatic updating of the immediate environment, but effortful updating of the more remote environment. In other words, automaticity of updating was asymmetric. When asked to update the remote environment, people automatically update the immediate environment; when asked to update the immediate environment, they do not automatically update the remote environment. The same asymmetry has been shown between real and imagined environments wherein the real environment was automatically updated and the imagined was not (Wang, 2004), supporting the idea that updating is based on importance. This asymmetry in updating, favoring proximal environments over larger-scale, more distal ones, illustrates cognitive efficiency and selectivity. The finding, though, does not mean that people *cannot* update across scales. In fact, through their procedure, Wang and Brockmole (2003a) showed directly that when asked, people can, with effort, update the distal, larger scale environment, even when physically situated within the proximal environment. Furthermore, Bilge and Taylor's (2006) work suggests that updating across scales is more likely to occur after learning from a map, as opposed to direct experience.

2.4 Through Language

One uniquely human symbolic system that can convey spatial information is language. By language, here, we are not referring to the diverse methods that non-human animals have for conveying information (e.g., scent, posture, movement, or vocal calls). What we mean by language is the use of verbal information, whether spoken, written, or signed, to convey idea units or concepts. This human-specific form of language is a direct and effective means of detailing spatial information to others. For example, we have all experienced situations in which a passing driver rolled down his window, asking for directions. Using spoken language (e. g., "Turn left at the next stoplight."), sign language, and perhaps even written tools (e.g., jotting down the name of a street), the driver can be directed to a destination.

Language can also be used to describe environments that an individual may never actually visit at any point. Indeed some of these environments may not actually exist, except in fiction. Descriptions of locations in fictional novels often detail relationships between objects, landmarks, and other geographic locations to such a degree that the reader can develop a fairly complex representation of the description. The reader will never have the opportunity to act on that representation and negotiate those environments (e.g., the terrain described in *The Lord of the Rings*, the locations described in a *Tale of Two Cities*,or the hotel depicted in *Psycho*). Nevertheless, the processes involved in constructing and updating such a representation bear many similarities to those necessary for building a spatial representation while navigating or studying a map. One difference, of course, is the degree to which an individual has physical, kinesthetic experience in those locations (similar issues arise with virtual environments). Such a difference, though, does not suggest that the underlying cognitive processes necessary for building, updating, and applying such a representation would be different in any systematic way.

Language, then, is an incredibly effective tool for informing the construction and updating of spatial representations. Language, in a way that is not intended as specific only to spatial experiences, has been described as a set of instructions that instruct the comprehender as to what, and how, information should be represented in memory (e.g., Givon, 1992). For example, references such as "he" and "they" indicate that prior information from the discourse should be reactivated and kept in current focus to ensure understanding of the current linguistic input. Thus, linguistic forms such as simple grammatical constructions (e.g., pronouns) all the way up to direct statements (e.g., "This next bit is important, so pay attention.") provide information about what readers should track and update. In situations involving spatial descriptions, processing instructions can include, as examples, spatial prepositions such as "next to," "toward," "go through," and so on. These prepositions indicate the direction (and type) of movement, the relationships between important landmarks and features of the environment, and the intended goal of spatial activity. Spatial prepositions are commonly used when individuals must determine how to get from one location to the next, the spatial relationships between particular locations, and the orientations and associations that comprise critical features of objects in environments. A considerable amount of experimental research has examined the use of such prepositions, in combination with general expectations that comprehenders have for orientations and perspectives (e.g., Carlson-Radvansky & Radvansky, 1996; Jackendoff & Landau, 1991; Landau & Jackendoff, 1993; Miller & Johnson-Laird, 1976).

How do comprehenders encode this information and combine it to construct a representation with which they might navigate environments, consider novel relationships, or simply think about described locations? Psycholinguistics, the psychological study of language use, has focused more generally on how any type of linguistic representation may be constructed. This general interest proves directly applicable for considering how individuals build representations for space. More specifically, work on text comprehension has assessed how language experiences influence representations, and the use of those representations to solve problems, in the domain of spatial cognition. In this section, we will consider three general topics that focus on how humans update their representations of space based on linguistic experience. These include the processes involved in building a spatial representation, the circumstances associated with resolving inconsistencies in such a representation, and the role of individual differences. We note that while this research is from the domain of text processing, the cognitive activities described are likely generalizable to a variety of discourse, and hence spatial, experiences.

The first issue to consider involves the ways in which comprehenders initiate and update their spatial representations. When we first receive some spatial information, whether it is based on a verbal description from a friend, a text or graphic description from a AAA travel guide, or even first-person movement through some environment, we may attempt to build mental structures that represent that information in memory. The goal of building such memory, of course, is to have some stored representation that can be retrieved at a later time point. Additionally, such structures should be updatable as novel information is encountered. Within psycholinguistics, one hypothesis as to how such structures are constructed (and potentially updated) comes from work on the gradual construction of memory. The structure-building hypothesis (Gernsbacher, 1990) contends that as new information is encountered, comprehenders build a new structure in memory to represent that information. With each new event and description, one of two general processes can occur. Either the existing representation can become more elaborated (usually when the new information is directly relevant or coherent with the previous information), or a completely new substructure must be built for the new information (such as when a new topic is introduced).

This hypothesis is directly relevant for considering spatial processes. Given that space is three-dimensional, yet language is two-dimensional, language users often describe space in a linear way (Levelt, 1989; Linde & Labov, 1975; Zwaan & Radvansky, 1998). This fosters the building and updating of a representation in line with the structure-building framework. Each piece of information (e.g., providing directions: "First, take University Avenue to Central. *Then* turn left near the supermarket.") is encoded with respect to previous information, in the hopes of building a representative mental structure (see also Haviland & Clark, 1974). Thus, comprehenders update their spatial representations by incorporating new information into existing structures.

The framework we have just described makes sense for cases in which information is coherent or in line with prior information. But what happens when new information is inconsistent with what we already know? For example, if we expect that a left turn will lead us to a particular location, but in fact it does not, how do we contend with such information? Work on mental models (e.g., Gentner & Stevens, 1983; Johnson-Laird, 1983; Kintsch & van Dijk, 1978) has addressed some of the processes involved in such updating. Mental models are complex, connected internal representations of external stimuli. What differentiates work on mental models from general work on memory traces has been the specific focus on mental models as (a) representing information beyond that which has been personally experienced or read and (b) mentally manipulable structures, in that they can afford the construction of novel inferences and information. To this first point, mental models encode relationships that have not been explicitly detailed. For example, if A > B, and B > C, we might generate the inference that A > C, even though such information was not explicitly described. A mental model facilitates such operations. Secondly, mental models can be manipulated as, for example, if you were asked to consider what your neighborhood might look like from an overhead or survey perspective, as compared to your familiar route perspective. Mental models are the representations we use to run such simulations, and they are invaluable as a method for constructing comprehension (Barsalou, 1999; Kahneman & Tversky, 1982). We should note that the structure-building framework relies on the notion of mental models, and research has explicitly associated that framework with the construction of mental models (e.g., Rapp & Taylor, 2004).

To return to the second issue, what happens when new information is inconsistent with the model we have built so far? For example, consider the following spatial description: (1) The coffee pot is to the right of the phone. (2) The iPod is to the left of the phone. Now consider a final statement: (3) The coffee pot is to the left of the iPod. This third statement cannot be true given the prior information (see Figure 4). Ehrlich and Johnson-Laird (1982) addressed this notion of inconsistency, finding that participants take longer to read outcomes that are inconsistent with their expectations (also see deVega, 1995 and Rapp & Taylor, 2004 for further discussion). These longer reading times suggest that readers are working to reconcile the apparent inconsistency. With respect to the structure-building framework, readers must either revise their previous model (to reflect that, perhaps, one of the objects was not in the right place or perhaps there were two iPods or coffee pots), or build an entirely new structure to account for the discrepancy. The goal, of course, is to maintain coherence between new and prior information (Kendeou et al., 2004). When coherence cannot be maintained, previous representations may be overwritten or ignored in favor of new, more valid mental models.

Figure 4. A spatial array on which a simple spatial description may be based.

A considerable amount of work on this issue of updating, both with consistent and inconsistent information, has been derived from research examining spatial descriptions in narratives (Bower & Morrow, 1990). We describe this work specifically not because it represents the only way psychologists have studied spatial cognition during reading, but because it represents a rich field of research that has examined how spatial updating directly impacts comprehension (e.g., Bower & Rinck, 2001; Morrow, 1994; Morrow, Greenspan, & Bower, 1987; Morrow, Bower, & Greenspan, 1989; Rinck & Bower, 1995; Rinck, Williams, Bower, & Becker, 1996; Rinck, Hahnel, Bower, & Glowalla, 1997; Rinck, Bower, & Wolf, 1998; Wilson, Rinck, McNamara, Bower, & Morrow, 1993). In this work, participants are often asked to memorize spatial layouts of buildings (for example map, see Figure 5), including objects found in each room. Following memorization, they read stories describing characters moving through the layout. Their reading is occasionally interrupted with probe word pairs naming objects in rooms from the layout. The task is to determine whether the objects would be found in the same room (i.e., were two objects located in a single room) or different rooms. Intriguing effects are obtained when participants are reading about a particular room but the probes name objects located in other rooms; readers take longer to make decisions about objects in rooms far from the current focus (e.g., the protagonist's current location) and out of sequence, as compared to rooms closer to that focus. Indeed, far and near are defined here not by Euclidean distance, but with respect to the functional organization of the rooms such as walls and doorways.

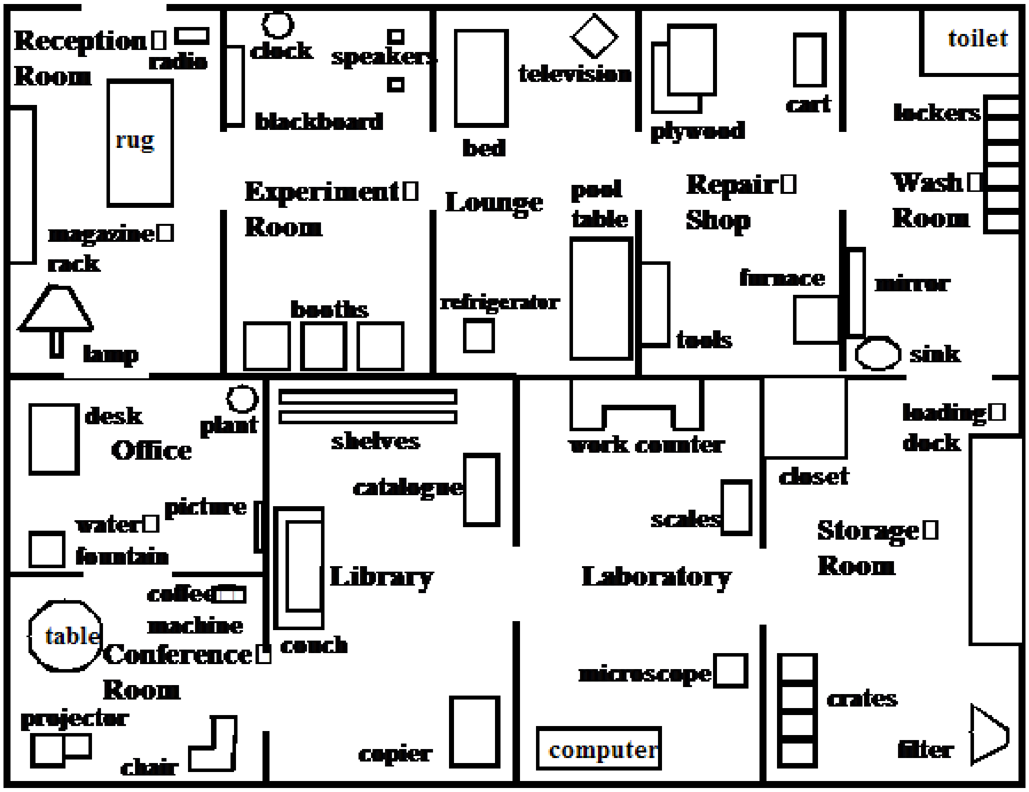

Figure 5. An example building layout, including rooms and objects within rooms learned prior to reading about a protagonist moving through the building. Such map stimuli were used by Morrow et al. (1987) and Rapp et al. (in press).

Thus, readers' representations of locations are influenced directly by the descriptions they read (i.e., the narratives), the knowledge they already possess (i. e., their memory for the studied map), and the current focus in the story (Rapp, Klug, & Taylor, in press). This set of results suggests that readers update their spatial representations on a moment-by-moment basis, reflecting the dynamic situations described in narratives. The activation of spatial information during reading likely fluctuates, in this way, over the course of a narrative (e.g., Kendeou & van den Broek, 2005; van den Broek, Risden, Fletcher, & Thurlow, 1996; van den Broek, Rapp, & Kendeou, 2005), potentially "out of sequence." So, updating is a process of these fluctuating activations influencing, and being influenced by, what people read (Rapp & van den Broek, 2005). Updating is the process of comprehending linguistic input by relying upon the activation of information in memory to facilitate coherent representations. These processes occur as readers build models of space.

Of course, not everyone can successfully update their memory and build strong spatial representations. This leads to a third core issue in the study of spatial updating through language - the role of individual differences. Consider that individuals possess diverse storehouses of prior knowledge, which as discussed earlier is recruited in attempts to navigate environments and understand space. For example, some readers may have more familiarity with the Boston area, and thus a description of local Boston landmarks may be more or less useful in understanding where to get the best ice cream in the city. While many accounts of spatial cognition have focused on individual differences in some inherent spatial ability (Allen, 2000; Gilmartin, 1986; Montello, Lovelace, Golledge, & Self, 1999; Voyer, Voyer, & Bryden, 1995), just as important is the notion of whether individuals posses prior knowledge that they can then apply to novel situations (van den Broek et al., 2005). For example, if one is familiar with a grid-like road layout, navigating New York's city layout would be simple; prior knowledge about city grids can facilitate expectations about how other grid-like city layouts work. However, knowledge about that system is less useful in cities without such a layout (e.g., Boston). So, individual differences in spatial updating can be a function of prior knowledge and experiences with spatial situations.

Additionally, individual differences need not just be a function of stored knowledge or inherited attributes, but also the particular circumstances surrounding a spatial experience. Related to this issue is a finding directly relevant to readers' general updating processes. Work has shown that readers do not spontaneously update their spatial models; instead, updating must be set as a specific task goal (Hakala, 1999; Morrow, 1994; Rich & Taylor, 2000). This suggests that spatial updating is not a privileged, automatic process while reading. Only when circumstances demand such updating, or individuals are specifically tracking the spatial constraints of a situation, are they likely to update their spatial models. Current work on spatial updating attempts to determine the linguistic cues that foster such updating, as well as how expectations may influence such processes (e.g., Rapp & Taylor, 2004). Overall, though, individual differences beyond proposed genetic bases for spatial cognition tend to exert a powerful role on spatial comprehension.

Obtaining spatial information through language is obviously a uniquely human endeavor. Human comprehenders rely on language for building and furthering an understanding of their environment. Indeed, comprehension is a function not only of direct environmental experience, but also indirect descriptions provided by others through writing, speech, and gesture. Just as one might build any physical structure, the mental processes involved in spatial comprehension entail the building of a mental structure that houses information about experienced and described environments. This research suggests that the processes that underlie spatial cognition, that of constructing a representation and updating that representation, seem to a degree invariant across a variety of discourse experiences.

III. Integrating Across Multiple Symbolic Sources

- Start out going South on E. Perimeter Rd.
- Turn right on Junction Way.
- Merge onto Bay Blvd. at the boat docks.
- Turn right onto Palm Rd.
- At the Island Information Center, merge onto Overlook Dr.
- Take a slight right onto N. Perimeter Rd.
- End at Whale Beach

Figure 6. An example of possible directions provided by internet direction/ map sites.

While psycholinguistics investigates the ways in which language influences spatial processing, many everyday experiences involve more than just the presentation of text in the service of learning about some environment. One trip to Mapquest.com or Yahoo Maps on the internet illustrates the common practice of combining spatial descriptions in text format with pictorial maps (see Figure 6). People mentally organize geographic space similarly whether they anticipate having to verbally or graphically reproduce the environment (Taylor & Tversky, 1992a), and they can make spatial inferences whether having learned the information from maps or from descriptions (Taylor & Tversky, 1992b). Yet, these two symbolic information sources differ in their inherent ability to present different information types. Maps naturally convey specific spatial information, both relative and absolute. Language naturally relates identity information (through labels) and organizational, including sequencing, information. Thus, maps combined with spatial descriptions (or vice versa) maximize the potential for conveying spatial information.

In fact, it is generally the case (Cohen, Johnston, McGee, Oviatt, Clow, & Smith, 1998; Wauchope, 1996) that a dual-mode verbal and graphic representation is preferable to a single mode presentation, as it may improve speed and accuracy of extracting information. Considerable work by Mayer and colleagues (Mayer, 2001, 2003; Mayer & Sims, 1994) has demonstrated that combinations of media formats (e.g., text and pictures) may facilitate learning. Analogously, such combinations may assist in the construction and use of reliable spatial representations. The caveat to this is that such combinations should not tax cognitive load (Mayer, Heiser, & Lonn, 2001), should not overwhelm perceptual processing (Tversky, Morrison, & Betrancourt, 2002), should be appropriate to the information content (Brunye, Taylor, & Rapp, 2005), and should match one's conceptualization of the information (Tversky et al., 2002).

IV. Development of Spatial Cognition

An important consideration for much of the topics under discussion in this chapter is the developmental trajectories that might influence spatial cognition. We have focused particularly on some of the types of updating that are involved in using spatial representations. However, the ways in which individuals at different ages might show more or less proficiency in spatial updating are only beginning to be considered (Newcombe & Sluzenski, 2004). For example, Uttal, Fisher, and Taylor (2006) illustrated how maps and spatial descriptions may be symbiotically combined to enhance mental representations. In their study, 8-year-olds, 10-year-olds and adults learned the layout of a six-room space, either from a verbal description or from a map, and were then tested on their configural and relative location memory. For the types of information tested, participants who learned from the map performed better than those who learned from the description. For those who learned from descriptions, while the ten-year-olds performed nearly as well as did the adults, eight-year-olds' mental models differed substantially. The 8-year-olds retained sequential information but did not infer the configural shape from the description. A second experiment showed the advantage in updating conferred by seeing a graphic with the description. In this study, participants of all ages first viewed a schematic map of the spatial layout. This schematic provided only layout information, omitting labeling and specifics about locations. Seeing the schematic facilitated 8-year-old's use of the description and improved their ability to infer relative locations that had not been specifically described. As this study demonstrates, insight into the development of spatial cognition can inform our understanding of the mechanisms that drive spatial updating.

V. Conclusions

Navigation through environments requires the capacity to encode information about what we experience. However, successful navigation, like successful problem solving, requires that those spatial representations be updated to incorporate new or changed information and to be used "out of sequence." Our opening example presented one common case for which this is important - revising our path to work or school to accommodate construction detours. While we must rely on memory to decide which streets we might take to get to work, we must also go beyond those experience-driven, route based perspectives to consider alternative paths to work when, say, a road is closed. Early research demonstrated that non-human animals engage in similar activities, determining shortcuts to retrieve a desired reward. Thus, across species, the ability to successfully build spatial representations is important for everyday survival.

Unlike those non-human animals, though, human spatial cognition represents a more complex set of processes and mechanisms that is designed to handle a diverse set of experiences, cues, and symbols. For example, symbolic representations, conveyed through pictures and language, can be used to build robust representations for spatial environments of many types. In fact, individuals can build vivid spatial representations for places they might never actually navigate, including both real-world (e.g., learning about a geographic region by reading travel guides) and fictional settings (e.g., becoming familiar with Hogwart's Castle layout from reading the *Harry Potter* series). Because humans gain information from multiple sources, the mental representation they form has been described as a cognitive collage (Tversky, 1993).

In this chapter, we have described how spatial representations are both constructed and updated based on a plethora of stimuli-driven, goal-driven, and participant-driven features. By understanding the mechanisms and influences on spatial cognition, we determine the underlying processes that guide spatial activity (e.g., memory updating, perspective taking, or problem solving). Additionally, that information may prove useful in the development of information delivery systems (e.g., GIS, on-line map services, or travel guidebooks) for helping individuals quickly and effectively build spatial representations (Albert & Golledge, 1998). In that sense, this work may inform the design of effective learning systems (Rapp, 2005; Rapp, Taylor, & Crane, 2003). Understanding how we build spatial representations, through direct experience and symbolic experiences, both in sequence and out of sequence, proves critical for both basic and applied settings.

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