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11

Spatial Memory of Real Environments, Virtual Environments, and Maps

Daniel R. Montello, Mary Hegarty,
and Anthony E. Richardson
University of California—Santa Barbara

David Waller
Miami University

SPATIAL MEMORY OF REAL ENVIRONMENTS, VIRTUAL ENVIRONMENTS, AND MAPS

As people move about the environment, they acquire knowledge about patterns of their own movement and about spatial relations among places in the world. This knowledge is encoded and stored in memory, allowing people to find the places again in an efficient manner and to communicate the locations to others. As they sit, stand, and travel in environments, people acquire spatial knowledge "directly" via perceptual–motor interaction with the world. But spatial knowledge is also acquired "indirectly" via external representations of the world and its spatial layout. We refer to these direct and indirect ways of learning spatial relations in the world as alternative sources for knowledge acquisition. For both theoretical and practical reasons, it is interesting to ask how the spatial knowledge acquired through different sources is similar and how it is different. To what degree are memory content, structure, and process similar or different when based on different sources, and why?

In this chapter, we review research on how people remember spatial relations in the environment as a function of the source through which the knowledge is acquired. We focus on knowledge of spatial properties (location, direction, distance, etc.) of large-scale environments that "contain" people and in which people locomote (Montello, 1993). Although it is difficult to delimit this range of scales precisely, it includes something like the space of rooms up to the space of large cities or perhaps even small countries. It is significant that such spaces often require people to integrate information (such as views of scenes) over considerable time periods as they move about and gain perceptual access to new parts of the environment. Our concern is not primarily with spatial relations in molecules, table-top arrays, or hand gestures, nor with spatial relations in the solar system. However, people acquire spatial knowledge about environments from representations at other scales; notably, people learn about environments from maps, and so we do discuss maps in this chapter as sources of environmental spatial knowledge.

People acquire spatial knowledge via several different sources (reviewed by Montello & Freundschuh, 1995). One may first distinguish direct from indirect sources. Direct sources are non-symbolic; they involve apprehension of spatial knowledge directly from the environment via sensorimotor experience in that environment. All other sources may be termed indirect, or symbolic (Gibson's [1979] term was "mediated"). They are symbolic because they transmit spatial information by exposing people to external representations or simulations of the environments to which they refer. Indirect sources include static pictorial representations, such as maps and pictures (3-D models of environments may be included here, as they are still primarily about the 2 dimensions of the earth surface). Also included are various dynamic pictorial representations, such as movies and animations. This class would include dynamic computer graphics, which are commonly called "virtual reality" or "virtual environments" when the viewer controls movement through the simulated environment. Finally, language, spoken or written (even sung—Chatwin, 1987), provides an important indirect source for learning spatial knowledge.

In this chapter, we consider research and theory on the nature of spatial memory resulting from learning via three specific sources:

1. Direct experience, particularly standing and walking,
2. Flat and static maps, and
3. Virtual environments of both the desktop and immersive varieties.

The first two sources are very common ways by which people learn space; all three are of great interest to researchers currently and over the last several decades. To begin, different sources lead to variations in spatial memory because of the different information they make available for encoding into memory. The sources do not provide exactly the same information about space, and they do not provide information in exactly the same format. Because of this, spatial memories from different sources must vary somewhat, at least in content. But do the three sources lead to different memory structures and processes? To answer we briefly review a framework for understanding memory structure and processes; we also consider empirical methods for studying memory, including their limitations. We then turn to two major issues in the research literature concerning environmental spatial memory structure and process: orientation specificity, and the distinction between route and survey knowledge. We finish the chapter with a set of conclusions about spatial memory as a function of the source by which it was acquired; we also consider some other approaches to the question of how spatial memory might vary as a function of the source from which it was acquired.

A primary concern of memory researchers during the last couple decades has been the conceptual and empirical characterization of different memory systems. Distinctions have been considered between procedural and declarative memory, episodic and semantic memory, implicit and explicit memory, and so on (e.g., Schacter & Tulving, 1994). These distinctions have hardly been considered in research on environmental spatial memory (Anooshian & Siegel, 1985, and Golledge & Stimson, 1997, provide rare examples). We do not believe the issues of orientation specificity and route-survey knowledge map well onto the concerns of general memory researchers. For example, route knowledge is sometimes described as procedural and/or implicit but in fact is often said at other times to consist of explicit knowledge of which landmarks follow which landmarks along a route, not just the procedural ability to actually follow the route. Similarly, I may know the direction straight back to the campsite either implicitly or explicitly. For this reason, we do not attempt in this chapter to characterize environmental spatial knowledge from different sources with respect to some of the common distinctions among types of memory systems made by general memory researchers.

CHARACTERISTICS OF THE SOURCES

Wilma is about to land at the airport in Santa Barbara, where she will start her freshman year at the University of California. Wilma is from Northern California, however, and she has never been to the Santa Barbara area before. She knows almost nothing about the layout of the area beyond an impression of the general appearance of the campus she acquired from looking at the university web site and a few plausible assumptions about the typical layout of medium-sized California cities. As her plane descends toward the airport, Wilma sees a chain of mountains to one side of the urban area and the glimmering Pacific Ocean to the other. She mistakenly infers, as many visitors do, that the mountains sit to the east of the city because the ocean view must be to the west; Wilma has never learned to interpret the sun's position carefully enough to realize her mistaken assumption. In any case, the beautiful surroundings captivate her more than a concern with the cardinal orientation of her new home. She does notice that the airport itself lies about a minute or two (which must be at least a few miles) beyond the largest urban area she sees; passengers around her are saying it's the actual city of Santa Barbara. Just before touching down, she also sees a cluster of buildings along the ocean cliffs that look like the picture of the campus she saw on the university web site. After she deplanes, she can still see some of the buildings on the campus. She realizes that the airport is very near the campus, and that both are right next to the ocean. For a moment, she wonders if her college dormitory window might even give her an ocean view. As she leaves the airport in a taxi, Wilma notes the pattern of the roads that lead from the airport to the campus and realizes that she could have walked there if she had been without luggage. Although the trip from the airport to campus is not long, it is rather indirect. But Wilma maintains a sense of the location of the campus relative to the airport because she can continue to see both places from the window of the taxi as she rides along. Wilma begins to develop knowledge of the spatial layout of her new home.

Wilma's first day in Santa Barbara demonstrates the spatial cognitive challenges and opportunities facing a person encountering a new place for the first time. She is exposed to information about the spatial layout via pictures, verbal comments, directly experienced views from different perspectives, and visual and proprioceptive perceptions of her own movement. Perceptual information is combined with prior expectations and initial assumptions in order to shape the spatial memories she is developing. Notably, Wilma is like the rest of us in that her spatial memories are based on a variety of sources of information, not just direct experience but various indirect experiences as well. As we noted above, the various direct and indirect sources provide somewhat different information about space, in somewhat different formats. Furthermore, within each class of sources such as direct experience, maps, and virtual environments, there are specific variants that may lead to different spatial memories because of characteristic differences in the information they make available for encoding into memory.

Types of Direct Experience, Maps, and Virtual Environments

Environments may be experienced directly in various ways—variations that pertain both to the sensory systems and the motor systems involved. For most people, vision is probably the main sensory modality for acquiring spatial knowledge at environmental scales, insofar as it affords apprehension of the most precise information at the greatest distances. But spatial information in directly experienced environments is acquired via other sensory modalities, especially the vestibular senses (linear and angular acceleration information), kinesthesis (limb position, force, and movement), and audition. In specialized situations, other sensory modalities, such as tactile pressure or temperature senses (wind or sun directions can be detected) may contribute to the apprehension of spatial properties. Perspective varies too. One may view a place statically from a single perspective or from several perspectives. Given a single, static perspective, one may view a place while standing in the street, or from the window of a tall building or airplane. Different modes of locomotion are used to get around the environment. One may locomote by crawling, walking, or running; one may locomote with mechanical aids such as bicycles, cars, or planes. Mechanically-assisted direct experience, such as riding in a car, must surely lead to the acquisition of different knowledge than does unassisted experience, such as walking (though no research demonstrates this definitively, to our knowledge).

As an indirect pictorial source of spatial knowledge, cartographic maps may take a variety of forms that could have implications for the knowledge that results from them. First, maps vary in scale. Smaller-scale maps show larger areas of the earth, such as continents or the whole planet; larger-scale maps show smaller areas of the earth, such as cities or neighborhoods. Besides the amount of earth surface depicted at different scales, smaller-scale maps tend strongly to be more generalized—they depict fewer features, in less detail, and more schematically. For example, rivers and roads are depicted as meandering more on larger-scale maps. A second relevant distinction is the difference between reference and thematic maps. Reference maps attempt to show perceptible features of the earth surface and relatively stable entities to be found there (lakes, mountains, cities, roads). They are meant to be more general-purpose, and they therefore attempt to depict information as accurately and completely as they can at a particular scale. Thematic maps are statistical maps; they attempt to show the spatial distribution of one or a few variables on the earth's surface, variables that may not be directly perceptible in the environment at all (e.g., disease rates). Thematic maps are specific in purpose and may reduce spatial detail to a minimum, though reference maps such as those designed for subway navigation (or those people sketch to give directions) may also be highly schematic, distorting and simplifying spatial properties such as metric distance. Third, although maps are usually thought of as flat and static, they may represent relief as in a 3-D model or change over time as in an animation. Fourth, maps often depict the earth surface from directly overhead, using a vertical perspective, but they sometimes depict from an oblique perspective. Vertical-perspectives are often orthogonal, showing all areas as if from directly overhead; oblique perspectives nearly always depict a single point-of-view so that more distant features are smaller and occluded. Perspective is part of the larger issue of projection, the particular geometrical or mathematical approach taken to making a flat picture from the spherical earth surface. Projection determines which spatial properties are distorted, and how, at various locations on the map (all flat maps distort spatial properties to some degree). Although we usually think of maps as visual displays, they may be designed for the tactile or even the auditory modalities. For most people, prototypical maps include small-scale reference maps (e.g., a map of the United States showing cities, rivers, and state boundaries) and medium- or large-scale navigation maps (see Vasiliev et al., 1990; Warren, 1995). Spatial cognition research has involved both of these types of maps, but has also included many studies with very large-scale and highly schematized map-like graphics (e.g., Fig. 11.1). Our review below focuses on these types of maps, though thematic maps and various types of non-map graphics do present spatial information (e.g., Hegarty & Just, 1993; Lloyd, 1988).

Virtual environments (VEs) also take a variety of forms that have implications for knowledge acquisition. VEs are interactive, real-time, 3-D graphical displays—computer-created simulations of places or environments that change appropriately in response to locomotion or other motor behaviors by users (active control). Virtual displays always include a first-person perspective, as if being viewed through the eyes (or heard through the ears, etc.) of someone moving through the space. The visual appearance of the simulated environment looks somewhat like what one would see in a real environment, and of course, the detail and faithfulness of this visual realism continues to increase with improvements in computer technology, etc. But this apparent realism is not very great in some virtual displays of today, and by itself, even great visual realism of this type would not qualify a display to be dubbed "virtual" (a photograph is almost never called "virtual"). Even given these definitional constraints, however, there are a variety of virtual systems that appear realistic to different degrees and in different ways. Just as it is important to characterize variations in the ways that environments are directly experienced and in the types of maps, it is important for our purposes to characterize aspects of different virtual systems.

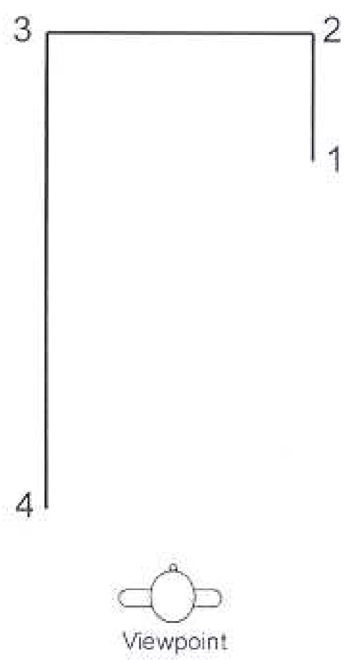

FIG. 11.1. Typical pathway used in orientation-specificity research by Levine, Presson, McNamara, Sholl, and others. (Adaptation of collaborative research—year not applicable.)

Different VEs include desktop displays, projected displays, caves, augmented realities, and fully immersive systems. Displays created by these systems vary in their size, their coverage of the visual field, and the sensory and motor systems they involve. A desktop VE presents the environment on a flat CRT screen before a stationary observer. Locomotion is usually accomplished through the use of a joystick or keyboard, which provide different efference copy and proprioceptive feedback from that provided by head or whole-body movement. Vestibular information provided from head and body rotations is unavailable. These types of VE are most similar to slide and video presentations. They differ from slides/videos in that they allow for active control of locomotion by the observer, but they also present the observer with images generally lower in fidelity than a slide or video. Another type of VE interface that affords a more direct form of interaction with the environment uses head-mounted displays (HMDs) and tracking systems to update head orientation, allowing the navigator to look around during travel. However, most of these systems do not track rotation of the entire body, which may or may not affect the way people acquire spatial knowledge from them. Instead, body rotation and translation is accomplished through a secondary manner such as using keyboard, mouse, or pointing with a data glove. These types of systems provide proprioceptive information regarding head orientation but do not provide such information regarding body heading. The most sophisticated VE systems allow for complete head and body tracking, allowing the observer to translate and rotate in space as they would in a real environment and producing interaction most similar to real navigation. These VEs are referred to in the literature as immersive or fully immersive VEs.

Information the Sources Provide for Encoding

Our review of various types of direct experience, maps, and virtual environments makes it clear that spatial knowledge will vary as a function of its source, at least in content. That is because different sources provide somewhat different information about environments. Montello and Freundschuh (1995) differentiated the sources they listed in terms of eight characteristics by which the sources differ in the way they present information to people. First, some sources present information in a dynamic stream, others present it in static snapshots; also, information about dynamic process may be presented statically or dynamically (compare arrows on maps to animations). Another difference is that sources such as maps present information in a way that supports relatively simultaneous pickup of information (though scanning a map requires eye movement and takes place over time, e.g., Dobson, 1979); most direct and virtual presentations require sequential pickup and integration of information over considerable time periods, though VEs can be designed to allow obstructions to turn invisible. Related to this, sources vary in the viewing perspective they provide, whether from a vertical perspective (a "bird's-eye view"), a horizontal or terrain-level perspective, or some oblique perspective in between. A fourth characteristic that differentiates the sources concerns the abstractness of their symbols (MacEachren, 1995). The need to interpret symbols clearly differentiates indirect sources like maps from direct sources (and many VEs) in the first place. However, among different indirect sources, there are variations in the degree to which symbols are iconic—Robinson & Petchenik (1976) called it mimetic—perceptually resembling what they stand for, versus arbitrary, not resembling what they stand for. Maps usually show distances in a very iconic way, for example, insofar as a distance between places in the world that is twice as far as another is shown as twice as far on the map (this is actually only approximately true on most maps, and is never perfectly true everywhere on any map because of the inevitable distortions of projection). In contrast, other map symbols represent quite arbitrarily; the hypsometric color changes that represent elevation changes do not particularly resemble different elevations (the very dry and low Death Valley is very green on such a map). Another characteristic that differentiates sources concerns whether a source is at the same or a different spatial scale than the environment, thus perhaps requiring scale translation for its comprehension; again, maps and direct experience provide the strongest contrast here, though desktop VEs typically display the environment on a small computer monitor. A sixth characteristic is the precision of the spatial knowledge presented (and represented) by a source. Spatial language is well known to represent spatial information quite imprecisely most of the time ("meet me next to the fountain"). Most maps present spatial information rather precisely; unfortunately this precision is frequently spurious, as when subway maps show precise distances that are not intended to be interpreted as such. A seventh characteristic differentiating sources for acquiring spatial knowledge is that they differ with respect to their inclusion of detail, some of which may be irrelevant to spatial problem-solving.

It is clear the various sources provide different information to be encoded into memory, and will thus lead to the acquisition of different quantities and qualities of spatial knowledge. They offer sensorimotor

access to information in different ways and supply information varying in precision, accuracy, and completeness. Some sources make explicit what others only suggest and still others simply do not provide. It is difficult if not impossible to learn the layout of very large spaces from direct experience alone, for example, unless that direct experience comes from the window of an airplane; maps are normally the only way most people ever gain access to this information. And because maps present distorted spatial relationships, especially at small scales (large areas), people who learn from them will learn distorted spatial relationships (e.g., Saarinen, Parton, & Billberg, 1996). Furthermore, different sources require more or less in the way of symbolic transformations to be made in order to understand the information they provide (e.g., some require scale translation and some do not). Such transformations are psychologically nontrivial and are definitely not carried out in the same way or to the same end by all people (e.g., Liben, 1999). Taken together, these considerations make it evident that spatial memories will not be identical when based on different sources.

The Role of Body Movement. For our purposes, one of the most significant variations in the spatial information the sources provide for encoding into memory may concern whether the source involves locomotion of the body and its concomitant proprioceptive sensing. Kinesthetic and vestibular sensing, and efferent copy from actively-controlled movements, provide information about the spatial pattern of one's own movement through the environment—information which people (and other animals) use to perform *path integration*, to update knowledge of their location relative to a starting location and surrounding features based on perceived body speed and direction (Loomis, Klatzky, Golledge, & Philbeck, 1999). Map use, by itself, does not involve locomotion, directly experiencing environments often does. VEs do not involve (real) locomotion if they are of the desktop variety, though they do communicate movement via optic flow. Some immersive systems do, although a completely mobile virtual system that allows for a full range and extent of locomotory movements is quite rare at the present time (no behavioral-science research has been reported with such a system yet).

Research supports the contribution of proprioception, particularly vestibular sensing, to updating one's knowledge of location (Potegal, 1982; Rieser, Guth, & Hill, 1986). Gale, Golledge, Pellegrino & Doherty (1990) had participants learn routes by walking or by watching a video. They found that walkers were better able to re-travel the route than were the video watchers, suggesting the value of proprioceptive and/or efferent information. Taking a neuroscience approach to the question of what proprioception adds to spatial learning, Péruch et al. (1999) compared the navigation performance of control participants and patients who underwent surgery because of unilateral defects in their vestibular systems.

Within days after the operations, the vestibular patients made shortcuts and retraced routes with greater error than did the controls.

A study by Klatzky et al. (1998) produced clear evidence of the contributions of vestibular sensing to spatial learning. They had participants travel along two legs of a triangular path depicted in a virtual environment. One group of participants actually walked the path while viewing the appropriate optic flow for translations along the legs and rotations at the turn, shown through an HMD. At the end of the second leg, participants turned their bodies to face the origin location, which was unmarked. These participants were quite accurate facing toward the origin and varied their facing directions appropriately for paths with turns of varying angular size. Two other groups of participants did not actually locomote, but only viewed the appropriate optic flow through the HMD. One of these groups, however, was rotated on a chair as they saw the simulated rotation at the turn in the path. They received vestibular information about the turn, in other words, and their performance facing toward the origin was only a little worse than the group who actually walked the paths. The third group also did not actually locomote, nor were they rotated in their chair; they only saw rotational optic flow. They thus received no vestibular information about the turn. Their performance facing toward the origin was much worse than the first two groups, and got much worse as the actual turn size increased. This last group turned to face the origin as if they were still facing in their initial heading. Thus, visual information alone without concomitant body rotation was not sufficient to induce egocentric updating, at least with respect to body rotations (see also Bakker, Werkhoven, & Passenier, 1999; Chance, Gaunet, Beall, & Loomis, 1998).

A recent study has found strong evidence that brings into question the importance of proprioceptive information in learning environmental layout. Waller, Loomis, and Steck (2001) had participants learned a 1-mile (1.6 km) route in one of three ways. One group viewed the environment normally from the front seat of a car driven by the experimenter. A second group sat in a lab room and viewed a video of the route recorded through the front window of the car. A third group also learned the route from the video, but they viewed it while sitting in the back seat of the car as the video was being shot (they could not see the route directly from the car). The second and third groups, therefore, received identical visual information about the route but only the third group received proprioceptive information about the route. Results showed more accurate memory for directions and distances by the first group, but no difference between the second and third groups. In other words, the vestibular information provided by body movement while sitting in the car did not enhance spatial-knowledge acquisition over and above viewing the video. This surprising result suggests that the proprioceptive information available while riding in a car added little or nothing to spatial learning, at least given the scale and pattern of this particular route. Waller, Loomis, and Steck (2001) interpreted their results as indicating that vestibular information does not much facilitate learning spaces this large, and pointed out that previous findings (like those reviewed above) were typically confined to rooms or building-size spaces. It remains likely that the kinesthetic and efferent information available during actively-controlled and non-mechanically-assisted locomotion, such as when walking, would improve spatial learning (Waller, Loomis, & Haun, in press).

QUALITIES OF MEMORY REPRESENTATION: STRUCTURES AND PROCESSES

In this section, we discuss structures and processes of memory that result from different sources of spatial knowledge about the environment. Most research attention has focused on two qualities of spatial memory representations that may vary across sources of spatial knowledge. The first is *orientation specificity*. An orientation-specific memory representation is stored in memory and accessed preferentially in a single orientation; an *orientation-free* representation would be equally accessible in any orientation . The second quality concerns the distinction between *route* and *survey* knowledge. Route knowledge is knowledge of a sequence of places or landmarks connected by locomotion patterns. It is "string-like" or one-dimensional. Survey knowledge is knowledge of a layout of places or landmarks and their direct spatial interrelationships (distances, directions). It is "map-like" or two-dimensional, and not restricted to spatial interrelationships along routes that have been traveled.

It is important to note that memory representations themselves cannot be directly observed behaviorally—they must be inferred from performance on tasks that depend on the stored representations. In a typical situation, a person learns the layout of an environment from some experience, such as walking in the environment, viewing a map, or interacting with a virtual rendition of the environment. Based on perceptual and encoding processes, one or more representations of that environment are stored in memory. This internal representation can include not only properties directly perceived but also properties inferred from perceived information. At some later time the person performs a task (outcome measure), such as wayfinding or giving verbal directions, that relies at least in part on his or her stored representation of the environment. The performance of this task may or may not involve some transformation of the internally stored representation, i.e., some additional inferences. It is in fact difficult to determine to what extent a person's performance on a given outcome measure directly reflects the stored memory representation as opposed to transformations of that representation made in response to task demands.

One method that has been used to infer qualities of internal representations is the measurement of response time in addition to accuracy on outcome measures. If two tasks require different amounts of the same transformation of the stored representation, then they should take different amounts of time to perform. For example, orientation-specific representations are inferred from *alignment effects*. After viewing a map with west at the top, for example, people store a representation of the map in memory that also has west at the top. When this memory is accessed, the top is assigned by default to the forward direction of view in the environment (Levine, Jankovic, & Palij, 1982, called it "forward-up equivalence"). Questions about directions on the map will be answered most quickly and accurately when they are phrased from this preferred perspective, for example, "point to the town hall from the courthouse, as if you were facing west." When people have to answer questions about directions between places on a map from a perspective other than that stored in memory, the response is slower and/or less accurate. In our example, that would be pointing between places as if you were facing east (or any other direction than west). The extra time and/or error when pointing from an imagined perspective other than the learned orientation is the alignment effect.

Another method of reducing ambiguity about qualities of internal representations is to observe performance over several measures. For example, route knowledge may be sufficient to perform some spatial tasks well, such as route re-traveling. It may not be sufficient to perform other spatial tasks well, such as pointing directly to nonvisible features in the environment. If a person can re-travel a route well but performs at chance level on a pointing task, it could be concluded the person has only an internal route representation. In reality, however, the pattern of performance over different measures is rarely as clear as this. For example, suppose a person can re-travel a route well, and his or her pointing accuracy is above chance but much less than perfect. This pattern of performance would result if the person had acquired some imprecise survey knowledge. However it would also result if the person could eliminate some possible pointing directions on the basis of route knowledge alone. Therefore the nature of the internal representation is ambiguous in this case. Detailed simulations of specific models for route (or survey) knowledge could address the question of the qualities of spatial representations necessary to support particular levels of accuracy and precision in observed behaviors, but very little of this work has been done (e.g., Dawson, Boechler, & Valsangkar-Smyth, 2000; Montello & Frank, 1996).

Researchers must therefore be cautious in assuming that a specific outcome measure necessarily reflects a particular type of internal representation. For example, the ability to draw a map of an environment has sometimes been viewed as evidence for an internal survey representation. However, although a map is a survey representation of an environment, a relatively accurate map can be drawn from an internal route representation that is quantitatively scaled, such that integration of the layout of segments and turns of the route occurs when the route representation is externalized in the drawing process. In such a case, the "survey knowledge" was not stored in memory but was created by inference during recall and task performance. Similarly, pointing to nonvisible locations is often viewed as a measure of survey knowledge. However, pointing from one's self to a landmark requires not only knowledge of the layout of the surrounds, but also knowledge of one's location and heading in the surrounds; it requires one's survey representation to be "egocentrically-oriented" (some other measures, such as sketch maps, do not require this). One's failure to point accurately could result from being misoriented (i.e. misrepresenting one's current heading), even with a perfect internal representation of the configuration of the environment. Thus, while patterns of performance over a number of different outcome measures (including accuracy and response time) can provide insights into the nature of people's internal representations, researchers must always be mindful that an internal representation might be transformed in response to task demands.

Orientation Specificity

Back on campus, Wilma has gotten out of her taxi and is walking back to her dormitory. She thinks she can find the dorm, even though this is her first visit to the campus, because she spent several minutes before she left home studying the campus map she received with her registration material. Wilma knows her dorm is near the most prominent landmark on campus, Storke Tower, and she also remembers that the dorm is below and to the left of the tower on the map. As she walks, she pictures the campus map in her mind. As is common with maps, the campus map is designed with north to the top, and Wilma's image is also oriented this way. She begins walking to left of the tower, but she gets confused for a few moments when she realizes she is walking south. She regains her sense of orientation and changes her walking direction, knowing that her dorm should be to the other side of the tower. Thus, Wilma clears up her encounter with the orientation specificity of spatial memories derived from maps.

Wilma experienced the effects of orientation specificity because her memory based on the campus map was recalled in the same orientation in which it was viewed. Maps, and memory images of maps, are accessed in a particular orientation. When the map information is used in an ongoing navigation task, it must generally be coordinated with the orientation of the local surrounds—the person's heading as she locomotes through the environment. The most common way to do this is to assume that "up" on the map is "forward" in the surrounds (Shepard & Hurwitz, 1984). When this assumption is not true, as in Wilma's case, either errors of movement from being misoriented or extra response time attempting to fix orientation, or both, result.

The question of the orientation specificity of spatial memory, including how it may differ for knowledge derived from different sources, has been a particularly active area of spatial-cognition research in the last couple of decades. The phenomenon of orientation specificity for memory representations was demonstrated by Evans and Pezdek (1980), who showed people a series of depictions of the names of three U.S. states. Participants were asked to judge whether these depictions portrayed the true spatial relationships among the three states. Evans and Pezdek found that people's times to perform this task were closely related to the degree to which the stimuli were rotated away from the canonical north-up orientation of a U.S. map. This suggested that the relative locations of these states were stored in memory in a preferred orientation—the orientation typically seen on a map—and that recognizing alternate orientations required additional mental processing, which took time. These observations are consistent with a conceptualization of memory for map-acquired geographic information as a depictive image constructed in working memory of a previously viewed map. When tasks demand it, the contents of such an imagined map are scanned, rotated, or otherwise transformed much as a real map would be. Of course, the underlying long-term memory code could be a set of propositions (e.g., Pylyshyn, 1981), as long as the propositions contained information that resulted in their expression in working-memory with a preferred orientation. Regardless of the underlying memory structures and processes, the findings of Evans and Pezdek, along with a host of subsequent studies (Boer, 1991; Levine, Marchon, & Hanley, 1984; MacEachren, 1992; Presson & Hazelrigg, 1984), have made the orientation specificity of memories for map-acquired knowledge one of the most robust phenomena in spatial cognition.

Evans and Pezdek (1980) also examined the orientation specificity of spatial memories derived from direct experience rather than maps. Although they found that memories for the relative locations of U.S. states were stored with a preferred orientation, they also reported that memory for the relative locations of frequently visited campus buildings showed little or no such orientation specificity. People answered questions about the configurations of campus buildings equally quickly regardless of the orientation in which the depictions were presented. Evans and Pezdek suggested that no particular orientation for the campus buildings was preferred in memory because, as is common for directly experienced places, their locations had been viewed in the environment from multiple perspectives. Thus, spatial information can be accessed more flexibly from memories of directly experienced spaces than from those of maps.

The idea that memory for large spaces is orientation free was most persuasively argued by Presson and his colleagues, especially Presson, DeLange, & Hazelrigg (1989). Like Evans and Pezdek, Presson et al. noted that direct experience of a space typically involves viewing it in multiple orientations, whereas maps are generally learned in only one orientation. In other words, the distinction between map learning and direct experience is commonly confounded by the ways in which these different sources of information are learned. To eliminate this confound, Presson et al. controlled the manner in which people learned spatial information from maps and direct experience. They asked participants to study several simple spatial layouts like those used by Levine et al. (1984) (see Fig. 11.1). Presson et al. presented the layouts at different sizes, referring to them either as maps of a larger environment or as paths in the environment itself. Importantly, participants were shown each layout from a single perspective only. This control allowed Presson et al. to focus on differences between learning from maps and direct experience independent of the effect of learning from multiple perspectives. A single trial went as follows: After viewing the layout, participants were blindfolded, and taken to the location on the path and faced in the heading specified by the test question. They were either walked or pushed in a wheelchair along a meandering route to get to the test location; Presson et al. did this to try to ensure that participants would answer from memory only—not from an updated perception of their new location and heading. After arriving at the test location, participants were asked to make judgments of relative directions based on their memories of the layouts (e.g., "You are at Location 1, and Location 2 is directly behind you. Point to Location 4"). Consistent with past results, the investigators found that when people learned about the space by viewing a small display (2 × 2 ft), their judgments of relative directions revealed large alignment effects; they were more accurate when the judgment involved imagining a view aligned with the perspective during study (i.e. the question involved a facing direction that was up on the display) than when it involved a view that was misaligned. However, Presson et al. found that when people learned about the space by viewing a large display (12 × 12 ft), their judgments of relative directions revealed much smaller alignment effects that did not reach statistical significance.

Presson et al.'s (1989) finding of an attenuated alignment effect with large displays added an intriguing wrinkle to Evans and Pezdek's (1980) contention that the source of spatial knowledge affects the way in which it is stored in memory. Presson et al.'s results suggested that orientation-free performance was not necessarily related to learning an environment from multiple perspectives, as Evans and Pezdek had suggested. Because memories for large spaces viewed from only a single perspective appeared to be orientation free, Presson et al. suggested that the nature of the learning medium itself—not the manner in which it is used—affects the way that spatial knowledge is represented in memory. Specifically, Presson et al. conjectured that a large space that surrounds the viewer and affords navigation (an *environment*) will be encoded in terms of the relationships among the objects in the environment, not in terms of the relationships between the viewer and the objects in the environment. Because it is not viewer-centered, this *allocentric* way of coding environments is orientation free and does not produce alignment effects when accessed. In contrast, spaces learned from symbolic sources such as maps will be remembered in relation to the viewer, like pictures. Because they are coded in terms of the viewer, such *egocentric* memories are orientation specific and produce large alignment effects when accessed. Presson and his colleagues regarded this distinction between directly experienced spaces and symbolically-experienced spaces as critical to understanding spatial memory, and suggested that these different ways of learning were processed by two separable memory systems. They coined the phrases "primary" and "secondary" learning to describe this distinction (Presson & Hazelrigg, 1984; Presson & Somerville, 1985).

The lack of alignment effects for large displays reported by Presson et al. (1989) proved difficult to replicate. Notably, a series of studies by McNamara and his colleagues (Diwadkar & McNamara, 1997; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Shelton & McNamara, 1997, 2001) has repeatedly found sizeable and statistically significant alignment effects with spatial arrays as large as those used by Presson et al. (1989). Roskos-Ewoldsen et al. (1998) tried to replicate Presson et al. (1989) closely, comparing performance on small and large paths like that in Figure 1. Unlike Presson et al.'s participants, however, those tested by Roskos-Ewoldsen et al. were wheeled to a center location, facing in the heading from which the paths had initially been viewed. Half were wheeled directly and half were wheeled along a very circuitous route. These researchers found alignment effects for both small and large displays, in both errors and response times.

Research by Sholl and her colleagues (Sholl & Bartels, 2002; Sholl & Nolin, 1997) and by ourselves (Waller, Montello, Richardson, & Hegarty, 2002) has also helped clarify the reasons for the variations in the results of different researchers. First, we point out in Waller et al. (2002) that some previous work purporting to show that large spaces are stored in an orientation-free manner in memory, such as the research by Presson and his colleagues, failed to include measures of response times; alignment effects are often revealed in pointing error but are sometimes reflected in slower responses that are just as accurate. A second consideration concerns whether participants are actually disoriented in the testing room—whether they are aware of their headings in the surrounds. If participants in fact maintain orientation (update) while traveling to a location that corresponds to the location and heading of test questions, as in the work of Presson and his colleagues, questions misaligned with the initially viewed perspective of the layout will not be misaligned with the updated representation. Presson et al. (1989) did not check how disoriented participants actually were; Roskos-Ewoldsen et al. (1998) suggested that Presson et al.'s participants may not have been effectively disoriented. Alternatively, if participants update while traveling to a location that corresponds to the initial heading from which the paths had been viewed, as in Roskos-Ewoldsen et al., questions misaligned with the initially viewed perspective of the layout will still be misaligned with the updated representation. Roskos-Ewoldsen et al. empirically verified that participants who were wheeled directly to the test location were able to point to a particular wall of the room 60% of the time. But even participants who were wheeled circuitously were able to point to the wall 39% of the time, which is statistically greater orientation than chance at 25% (N = 66). To the degree that they had maintained orientation, participants would show alignment effects because they were answering misaligned questions from a misaligned heading. (Sholl & Bartels [2002] offer the interesting hypothesis that updating participants will be exposed to multiple "virtual" views of the path layout as they are circuitously moved about. Such imagined views of the path, according to these authors, would constitute the kind of multiple exposures that Evans and Pezdek [1980] had argued produces orientation-free memory).

Alternatively, if people do become thoroughly disoriented while traveling to the test location (as intended by the several researchers who have used circuitous blindfolded transport), people will be located and facing as required by the test question but will be unaware of this. Test questions will not be aligned or misaligned with the orientation of the person's working-memory representation because they have no oriented representation of their heading—they are disoriented. In such a case, according to Waller et al. (2002), all questions will be answered with nearly the same speed and accuracy. This will be less quickly and accurately than aligned questions, and more quickly and accurately than misaligned questions, are answered by a person who is oriented to the surrounds. In fact, orientation specificity is still revealed in this situation: A persistent influence of the learned perspective in disoriented participants results in alignment effects, though they are significantly weaker than those found with oriented participants who stay at the initial viewing location. Consistent with this, the alignment effects reported by Roskos-Ewoldsen et al. (1998) were smaller in both time and error (though not significantly) among participants who were wheeled circuitously than among those who were wheeled directly.

It thus appears that spatial memories based on single views are stored in an orientation-specific manner, whether based on maps or environments. Viewing spaces from multiple perspectives during learning will lead to an attenuation or elimination of alignment effects. This is true whether the source of spatial knowledge is directly experienced environments (Evans & Pezdek, 1980) or cartographic maps (MacEachren, 1992). There are two possible explanations for the fact that memory based on multiple views shows attenuated alignment effects. One is that learning spatial knowledge from multiple views leads to the creation of orientation-free representations. A second explanation suggests that even spatial memories acquired from multiple views are in fact orientation specific, whether based on direct experience or on maps. But when people are exposed to multiple views, they store multiple orientation-specific representations. Tasks that demand the adoption of a given perspective on the space either activate a previously experienced view that is aligned with the question, or they lead to interpolation between separate views that were previously experienced. Although not completely resolved yet, most contemporary evidence favors the hypothesis that spatial memories based on multiple views are stored in multiple orientation-specific representations, at least during early stages of learning (Diwadkar & McNamara, 1997).

However, even if spaces of all sizes are stored in an orientation-specific manner, there are still ways that knowledge sources at different scales may lead to differences in memory for space, though they may not be fundamental structural differences. In all three of Presson et al.'s (1989) experiments, participants produced much larger alignment effects (in error) with small displays than with large displays. Roskos-Ewoldsen et al. (1998) also found smaller alignment effects with circuitously-wheeled participants on large than on small displays, though the 11° difference was nonsignificant. Whether participants maintain or lose their orientations to the surrounds during circuitous transport to test locations, it remains the case that memories based on viewed displays of different sizes may be accessed somewhat differently. This may be a greater persistence of remembered views from small displays, or a lesser tendency to update within knowledge based on small displays. These possibilities await further research.

Orientation Specificity in VEs

To the degree that the distinction between primary and secondary spaces is important for understanding the nature of spatial memory, then knowledge derived from experience with virtual environments presents an interesting case. VEs have an intrinsically dual nature. On one hand, VEs are typically shown on small-scale display devices such as computer monitors or HMDs that are capable of being viewed entirely from one perspective. In this sense, VEs may be perceived as presenting a series of small-scale pictures to an observer who remains outside of the display. On the other hand, these display devices, particularly those with HMDs, can give a user the impression of being surrounded by a large-scale environment—they can induce *presence*. The dual nature of VEs is that they are at once representations of environments and environments in themselves. Researchers have noted that VEs might be regarded more as primary than secondary sources of spatial information (Liben, 1997; Wilson, 1997), yet this potential clearly relates to the quality of the VE system. For example, immersive VEs that surround the user with perceptual information and preserve natural means of interacting with space may be much more engaging and likely to be treated as a "primary" spaces than are desktop VEs.

In the last few years, several studies have examined the orientation specificity of spatial memories derived from experience in VEs. Despite wide differences in the quality of the VEs used, ranging from relatively simple desktop systems (e.g., Albert, Rensink, & Beusmans, 2000; Christou & Bülthoff, 1999; Richardson et al., 1999; Rossano et al., 1999) to more advanced systems that employ motion tracking and head-mounted displays (Miller, Clawson, & Sebrechts, 1999; Clawson, Miller, Knott, & Sebrechts, 1998), most studies have found evidence that memory for spatial information that is learned from a VE is orientation specific. For example, Christou and Bülthoff (1999) asked participants to explore a detailed computer model of a building, searching for several prominent landmarks. The position and orientation of the participants' viewpoint during the search was continuously recorded. This enabled the experimenters subsequently to show participants three kinds of images from the environment that they had learned:

1. Views of the landmarks they had actually seen,
2. Views of the landmarks that were oriented differently from what they had seen, and
3. Views that were mirror images of what they had seen.

The results clearly showed that participants were faster and more accurate in recognizing views that were previously seen than those that were not. Memories for these landmarks were stored simply as experienced views. These memories thus had a preferred orientation—that of the viewpoint during learning. Several other studies have also shown a preferred orientation for memories of VE spaces. In some cases, the preferred orientation is the one that was experienced at a particular location in the simulated space while it was explored (Albert et al., 2000; Clawson et al., 1998; Miller et al., 1999). In other studies, the preferred orientation appears to be one that is aligned with the initial view of the participant during learning (Richardson et al., 1999; Rossano et al., 1999); that is, people learning a complex environment from a VE sometimes use the orientation of the initial segment as a preferred orientation for the storage of spatial information for the rest of the layout. And some evidence suggests, like the findings of Evans and Pezdek (1980), that when people are given multiple views of a virtual environment, such as might occur during extended free exploration, alignment effects weaken (Rossano & Moak, 1998).

Survey vs. Route Knowledge

Returning once more to the story of Wilma's first day at UCSB, we find that she has unpacked her luggage at her dorm room. Now she wants to get a bite to eat, so she heads out of her room to walk over to the University Center where restaurants are located on campus. Wilma does not remember seeing this building on the campus map, but she does remember walking past it soon after getting out of the taxi. For a moment, she considers which way to walk. She knows she could probably backtrack along the route she walked to her dorm, but she also knows that may not be the shortest way. As she thinks about the route, Wilma imagines a sequence of views she had along her walk and specifically remembers a couple of turns she took to get to the dorm. But she does not feel confident that she can remember the entire route well enough to try and take a shortcut to the University Center. Instead, she decides to backtrack, but she will pay attention to the turns in her walk and the landmarks she will see along the way so she can start to figure out the direct spatial relationships among places on the campus. In this manner, Wilma will continue to acquire not just knowledge of specific routes between places, but an understanding of the two-dimensional configuration of the campus.

Wilma's knowledge of the route she walked is essentially a temporally connected linear series of views and movements, but she aspires to learn a more two-dimensional understanding of spatial layout so she can travel more efficiently from place to place. This is the distinction between route and survey knowledge, which has a long history in the spatial-cognition literature (reviewed by Montello, 1998). The distinction has in fact been conceptualized in somewhat different ways by various researchers, and it is thus difficult to draw conclusions about whether a person has route or survey representations stored in memory. Route knowledge is typically defined as an internal representation of the procedures necessary for finding one's way from place to place. This is sometimes conceptualized as a set of stimulus-response pairs, or a sequence of landmarks, with little or no intervening distance information, and perhaps imprecise turn instructions (ahead, left, right). Route representations are thought to be highly constrained and rigid, allowing wayfinding only along known pathways, typically in only one direction (e.g., Kuipers, 1978). Although they may be efficient for rapidly navigating well-known, unchanging environments, their fixed, sequential nature makes route representations impractical for creating novel paths or shortcuts, or for navigating in a changing environment. Most models of route knowledge suggest it contains little quantitative information about distances and directions. However, some researchers allow route knowledge to include quantitative information about distances and directions, as long as it is restricted to the "string-like" space of the route, and not the space across or between routes. In contrast, survey representation (or "configurational knowledge") is a more flexible form of spatial knowledge. Often conceived of as a "map in the head," survey representations allow direct access to quantitative spatial relationships, such as distances and directions between arbitrary locations in an environment—not solely those locations between which one has traveled. This way of representing information facilitates spatial inference and can be more accurate over longer distances (Thorndyke & Hayes-Roth, 1982; Sholl, 1993). Another aspect of the route-survey distinction of concern to some researchers is the perspective of the representation. Route knowledge is thought to be horizontal, from the terrain-level perspective of a traveler; survey knowledge is thought to be vertical, from a bird's-eye or orthogonal perspective (the latter is without a single viewpoint, but as if from directly above at all points). Clearly, though, one may know or not know the direction to a nonvisible target whether one accesses that from memory as if seeing through walls or as if floating above the space.

One factor that should facilitate attaining survey knowledge is familiarity—the amount of exposure one has to an environment. It is commonly thought that survey representations that are acquired by direct experience require time to develop. This view was put forth in a highly influential work by Siegel and White (1975), who synthesized much of the then-existing research on large-scale spatial representations in memory. They posited a "main sequence" of changes in mental representations of environmental space over time, from knowledge of landmarks, to knowledge of routes, to survey knowledge. Siegel and White suggested this sequence occurs both ontogenetically, from birth to adulthood, and microgenetically, from first to later exposures to a new environment over the course of time. This developmental hypothesis has been widely influential (Montello, 1998, called it the "dominant framework"), so that survey knowledge has usually been thought to be predicated on more rudimentary forms of spatial knowledge, such as knowledge of routes and landmarks.

Yet some evidence has raised questions about the degree to which survey knowledge requires comprehensive familiarity with an environment. Several investigators have concluded that survey knowledge can be formed quickly (Montello & Pick, 1993), even upon one's initial exposure to an environment (Holding & Holding, 1989). There is no question that over small areas, people can and do extract quantitative information about distances and directions (much of this evidence is reviewed by Montello, 1998). For instance, Loomis et al. (1993) demonstrated that blindfolded people can keep track of the distance and direction back to their start location with nonrandom accuracy after short walks including one or more turns (see also Sadalla and Montello, 1989). There is some evidence that survey knowledge can develop rapidly even in very large, complex environments. For example, Montello and Pick (1993) led participants twice along a complex route (approximately 500 meters with 15 to 20 turns) inside and outside of a large building. The accuracy with which participants were later able to point to the locations on this route led the researchers to conclude that at least some participants had formed survey knowledge of the area in less than half an hour. This and similar results have led many theorists either to discount the status of landmarks, routes, and survey knowledge as distinct entities, or at least to discount their status as a strict developmental sequence, instead considering them as more-or-less independent forms of spatial representations that develop concurrently (Foley & Cohen, 1984; Hanley & Levine, 1983; Montello, 1998; Schmitz, 1997). Of course, the finding that some people can quickly acquire survey knowledge from navigating large spaces does not mean that familiarity with the environment does not play an important role in establishing survey knowledge. Many contemporary investigators would agree that although it may be neither necessary nor sufficient for acquiring survey knowledge, familiarity with an environment does facilitate it.

In addition to familiarity, two other factors—field of view and the allocation of attention—have also been linked to the acquisition of survey knowledge. Using concepts from J. J. Gibson (1979), Sholl (1996) noted that a person's peripheral vision is instrumental in extracting the invariant spatial structure of an environment and proposed that peripheral vision is thus necessary for acquiring survey knowledge. Sholl examined this hypothesis by having participants learn an environment either naturally or with goggles that limited their field-of-view (restricted to the central 5°). When subsequently tested on their knowledge of the environment, participants in the full-vision group pointed between locations with patterns of error that were unrelated to the complexity of the route that connected the locations, suggesting to Sholl that they had formed survey knowledge. Participants who learned with the limited field-of-view apparently did not acquire much survey knowledge. Sholl concluded that when peripheral vision is unavailable, survey knowledge cannot be acquired. A wide field-of-view is thus necessary for developing a survey representation of a space.

The allocation of attention has also been linked to the acquisition of survey knowledge. There is some evidence that survey knowledge does not arise automatically, even after adequate exposure, but that it requires conscious attention to the environment during learning. In a series of studies, Lindberg and Gärling examined the degree to which conscious, effortful attention was required in order to learn the spatial characteristics of an environment (Lindberg & Gärling, 1981, 1983). In one experiment, Lindberg and Gärling (1981) asked people to walk through the corridors of a building, along paths of varying complexity. Participants were stopped periodically during the trip and asked to point and to estimate their distances to a previously passed location. One group of participants was required to perform a concurrent backward-counting task as they learned the environment. Another group had no such concurrent task and was thus able to devote more of their central, controlled processing to maintaining their orientation and learning the environment. Lindberg and Gärling (1981) found that while all participants were able to acquire knowledge about the routes that they had walked, those participants who were engaged in a secondary task during learning were less able to keep track of where the learned locations were. While these findings are often interpreted to mean that people acquire route knowledge more automatically than survey knowledge, some recent evidence by Allen and Willenborg (1998) suggests that route knowledge requires some conscious effort to acquire as well.

The two factors of attention and field of view may in fact be related. Sholl has speculated that the mechanism by which attention to a secondary task, such as backward counting, interferes with the acquisition of survey knowledge involves a functional restriction of one's field of view. She suggests that a secondary task usurps cognitive resources that might otherwise be used to process visual information from the periphery (see also Miura, 1990; Williams, 1982). Regardless of whether attention or field of view represents the more fundamental underlying mechanism, it appears likely that both influence the acquisition of survey knowledge.

Route and Survey Knowledge from Real World Navigation and Maps. Maps can be considered artifacts that facilitate the acquisition of survey knowledge—they eliminate the need for familiarity. They explicitly and immediately provide a survey representation of the global structure of an environment, and reveal spatial relationships that may not have been realized from direct experience. Unlike directly experienced environments, which surround people and are viewed while locomoting, maps provide a "survey overview" of an area, depicting quantitative spatial relations among places and features. The power of maps to depict survey relationships becomes especially important in the case of "gigantic" spaces such as countries and continents (Montello & Golledge, 1999); without maps, people would probably never come to realize the shapes of large earth features and their spatial interrelations.

Although we may think of maps as providing a replacement for extended direct experience, it was suggested some time ago that survey knowledge from a map is not equivalent to survey knowledge gained from direct experience. A classic study by Thorndyke and Hayes-Roth (1982) pointed to some differences between spatial knowledge learned from maps and from direct experience. The researchers compared performance by two groups of participants on tasks that required either route or survey knowledge of a large building. The first group consisted of people who had worked in the building for some time, from one month to two years, and had presumably learned the layout directly by traveling around its hallways (called "navigation" learners). The second group of participants had never visited the building; they learned its layout by studying a map of it for approximately one hour. Participants estimated straight-line distances directly between places in the building and route distances along corridors. Consistent with the idea that maps provide direct access to survey relationships, map learners estimated straight-line and route distances equally accurately, whereas navigation learners estimated route distances more accurately than straight-line distances. Map learners were less accurate than navigation learners in pointing to targets from various places in the building, but were more accurate in placing targets on a map of the building. Thorndyke and Hayes-Roth (1982) concluded that studying a map allows people to acquire survey knowledge of the environment, knowledge they can use to estimate straight-line distances by simple recall processes, such as image scanning, without the need for more complex inferences. Map learners make more errors in pointing to nonvisible targets because they must translate the vertical perspective of the map to a horizontal one. In contrast, navigation learners develop primarily knowledge of routes connecting places in the building. This allows route distances to be recalled without complex inferences, though simple manipulations such as adding up lengths of separate segments may be required. Navigation learners must use more complex inferential processes to determine straight-line distances from route knowledge.

The ability of people to acquire survey knowledge of complex environments through direct experience may also be limited by the complexity of the layout. Moeser (1988) studied the cognitive-mapping performance of participants who had worked in a hospital building with a complex configuration. In one experiment, participants were nurses who had either 4 or 25 months of experience in the building. Moeser asked these nurses to draw sketch maps of the layout of four floors. Analyses showed that none of the sketch maps bore close resemblance to the actual layout and that over 50% of the objects depicted on them were located in error. In another experiment, a different group of nurses who had worked in the building were compared to a group of participants who had never visited the building but learned it by studying a map. Map learners memorized the layout of the floors and were tested until they could place all of the names of items in their correct location on a floorplan. Map learners were then given a guided tour of each floor, following their progress with a map. This guided tour confounded participants' map knowledge with direct experience, limiting the comparison between the two groups. Nevertheless, Moeser's results illustrated the efficacy of map experience. Map learners were substantially more accurate than the nurses at pointing to targets (though they also estimated route distances more accurately). Even after two years of working in the building, nurses (who had presumably never seen a floorplan) had very poor survey knowledge of the extremely complex building layout. Moeser's findings demonstrate the power of maps to provide survey spatial information (see also Lloyd, 1989). They also suggest that maps may even be necessary for survey-knowledge acquisition if the environment is very complex.

When the layout of an environment is easier to apprehend, differences between map and direct-learning experience may diminish. Richardson et al. (1999) had participants learn the layout of two floors of a university building. Each floor consisted of three corridors; the corridors on each floor overlapped. Map and direct learners were given equal amounts of exposure—approximately 10 minutes. Results showed that both groups performed relatively accurately, and that there was no difference in error pointing between landmarks for the map and direct learners. There was also no difference between groups in their ability to estimate route distances; however, the map learners performed better at straight-line distance estimation. These findings suggest that for initial learning of a relatively simple environment, survey knowledge formed from a map may be quite similar to that formed from direct experience.

Route and Survey Knowledge From Virtual Environments. Unlike maps, which represent environments with abstract symbols, VEs represent them by iconic simulation. As Hunt and Waller (1999) point out, simulations of environments, in general, do not require that users consciously interpret spatial information to the degree that is required by more abstract representations of environments. Thus, VEs and other environmental simulations such as slideshows, 3-D models, and motion pictures, offer users a more naturalistic medium in which to acquire spatial information, and potentially allow users to devote less cognitive effort to learning spatial information than required by maps. In the decades preceding the advent of VE technology, several studies investigated spatial knowledge derived from a variety of less technologically sophisticated simulations, such as photographs or movies. Much of this research illustrated how readily people can learn spatial information from relatively impoverished sources, and how people use schemata to organize their mental representations of space. It also showed that real-world spatial cognition can be effectively studied using environmental simulations, though questions remained about aspects of the simulations that might not simulate direct experience accurately. In particular, these earlier simulations generally lacked whole-body movement, active control of simulated locomotion, and a full field-of-view. As discussed above, these aspects may have implications for the acquisition of survey knowledge. The shortcomings of earlier simulations are overcome to a large degree by features that VEs offer: interactivity, and in some systems, immersion and whole-body movement. By allowing users to interact in real time with an environment that apparently surrounds them, some investigators have claimed that VEs have the potential to be more effective than previous simulated environments, both at enabling people to learn about spaces and in enabling researchers to understand human spatial cognition in the real world (see, for example, Loomis, Blascovich, & Beall, 1999; Wilson, 1997).

There is now ample evidence that people are capable of acquiring route knowledge from experience in VEs. For example, Ruddle, Payne, & Jones (1997) examined people's spatial representations formed from desktop VEs by replicating Thorndyke and Hayes-Roth's (1982) classic study. Ruddle et al. had participants learn the layout of the same floorplan as in Thorndyke and Hayes-Roth's original study. After nine daily learning trials, participants showed similar levels of distance estimation, pointing, and navigation ability as did participants who navigated the real-world building in Thorndyke and Hayes-Roth's original study. Ruddle et al. concluded that, given sufficient experience, people are able to learn the spatial characteristics of a VE in much the same way that they learn from the real world. Similar research by other investigators has reached the same conclusions, especially with respect to the use of VEs to acquire route knowledge (Bliss, Tidwell, & Guest, 1997; Waller, Knapp, & Hunt, 2001; Witmer, Bailey, Knerr, & Parsons, 1996).

The degree to which VEs enable users to acquire survey knowledge is currently less clear. From a theoretical point of view, there are several reasons to believe that people may have difficulty acquiring survey knowledge by navigating in VEs. In the first place, many people have difficulty acquiring survey knowledge in the real world. For VEs that attempt to simulate the real-world faithfully, one would expect that survey knowledge acquisition from a VE would be at least as effortful and time consuming as in the real-world. As we have seen, the acquisition of survey knowledge is typically considered to require the learner's attention. We have also argued that VEs, inasmuch as they are simulations of environments, demand fewer conscious cognitive resources to interpret them. Perhaps it is because VEs elicit relatively little conscious effort in their interpretation that they do not lend themselves to acquiring survey knowledge. Moreover, VEs can place additional demands on users that are not present in the real world that may make acquiring survey knowledge even more difficult. For example, many of today's VE interfaces are arbitrary or unintuitive (e.g., clicking a mouse to move forward), and require a navigator to enlist conscious cognitive resources in order to use them. The effort required to use a VEs interface will thus likely detract from the acquisition of survey knowledge (see Waller, 2000). Additionally, we have seen that survey knowledge acquisition may require a wide field-of-view. Yet current VE systems do not typically offer very wide fields-of-view because they are computationally expensive. If survey knowledge acquisition is indeed facilitated through stimulation of one's peripheral vision, then current VE systems may make survey knowledge acquisition more difficult than it is in the real world. And as we reviewed above, the lack of whole-body movement, particularly body rotations, found in many VE systems, may impede the acquisition of directional knowledge. In this regard, even systems that respond to head rotations may be a considerable improvement over systems that utilize only a keyboard or joystick.

Despite the potential difficulties that VEs may have in enabling the acquisition of survey knowledge, a handful of studies have suggested that it is possible, especially when the spaces depicted are relatively small or simple in layout (Colle & Reid, 2000; Richardson et al., 1999; Rossano et al., 1999; Waller et al., 2001; Witmer, Sadowski, & Finkelstein, 2002). For example, the study by Richardson et al. (1999), discussed above, included a third group of participants who learned the two-storied building from a desktop VE, in addition to the map and walk groups. Participants did not differ in either their distance- or pointing-estimation accuracy within the same floor, suggesting that similar types of spatial knowledge had been acquired among the groups. However, VE learners performed the worst on direction and distance estimates that required an integrated understanding of the two floors. Sketch maps by these participants suggested that they fared much worse than the other two groups in reconciling the relative vertical orientations of the two floors because they were confused about the body rotations they took while "climbing" the virtual stairs between the floors. This points to the special difficulty of combining separate "pieces" of environments into an integrated representation, as suggested for decades by theory and data on the acquisition of spatial knowledge (Montello & Pick, 1993; Siegel and White, 1975), particularly in desktop systems when people do not actually turn their bodies during "locomotion." Such pieces might be separate floors, as in the example, or rooms, neighborhoods, route segments, and so on. Colle and Reid (2000) also demonstrated the difficulty people have learning configural relationships among multiple rooms in a desktop VE.

SUMMARY AND CONCLUSIONS

Knowledge of spatial relations in the environment is acquired and stored in memory for later retrieval and use. Memory representations are based on direct sensorimotor experience in environments but also on indirect sources such as maps, language, and virtual displays. It is both interesting and practically useful to ask how spatial memory based on different sources is similar and how it is different. To begin, sources of spatial knowledge present information differently. Directly experienced environments may be sensed through vision, audition, proprioception, or other senses to lesser extents. They may be viewed statically or dynamically during locomotion, and they may be experienced with or without the aid of machines like cars or planes. Likewise, maps vary in scale, whether they are reference or thematic maps, degree of schematicity, dimensionality, perspective and projection, and other ways. Virtual environments also take a variety of forms, including desktop, augmented, and immersive systems. These variations lead to characteristic differences in at least the content of memory based on different sources, because they provide different information for encoding into memory.

Especially noteworthy is the fact that different sources involve body movement in different ways and to different degrees. Sources that depend on whole-body locomotion provide proprioceptive and efferent information and take advantage of updating systems that allow mobile organisms to integrate movement information so as to maintain orientation. While several studies point to the role of body movement in spatial-knowledge acquisition, an important recent study suggest limits to the role of vestibular sensing at environmental scales. Ongoing research in a variety of labs will undoubtedly help clarify this in the near future.

Although the sources certainly lead to characteristic differences in the content of memory, it is not clear that they affect memory structures and processes more fundamentally beyond that. Two issues have been central to the question of whether memory structures and processes vary with spatial knowledge sources. The first concerns *orientation specificity*, whether spatial memory representations are stored and accessed preferentially in a particular orientation, usually the orientation from which a spatial layout was viewed during learning. Given the totality of the data, the most plausible hypothesis is that spatial memory, whether derived from maps, VEs, or direct experience, and whether it represents large or small spaces, is stored with a preferred orientation. This is particularly evident when one includes measures of response time as well as measures of response error. Most contemporary research finds little support for the notion that the medium through which spatial information is learned affects the orientation specificity of memory, though some evidence remains that body movement and spatial memory may not interact in exactly the same way for spaces of all sizes. The preferred orientation observed is typically that of the viewer's perspective during learning, suggesting that spatial memory is commonly stored by means of an egocentric *(viewpoint-dependent)* reference system. Other work has shown that the structure of the environment (Shelton & McNamara, 2001; Werner & Schmidt, 1999) and the structure of the learned spatial layout itself (Mou & McNamara, 2002) can affect the reference systems used to store spatial relationships. An intriguing possibility for future research is that speakers of languages without egocentric spatial terms might think about space in fundamentally different ways (Levinson, 1996) and would not show egocentric orientation specificity.

A second issue central to the question of whether memory structures and processes vary with spatial knowledge sources concerns the distinction between *route* and *survey* knowledge. Route knowledge is conceived to be more one-dimensional, less quantitative, and less flexibly accessible; survey knowledge is the opposite. In fact it is difficult to evaluate the validity of the route-survey distinction, and whether sources lead differentially to one or the other, insofar as the concepts have not been clearly and consistently defined in the literature. Conceptual and empirical arguments clearly support the special ability of maps to support the formation of survey knowledge, particularly over brief time periods of minutes or hours. At the same time, maps do not facilitate the acquisition of route knowledge the way direct travel does (albeit as reflected in a person's ability to follow routes in the real world). Evidence also supports the acquisition of survey knowledge from direct and virtual experience, and suggests the likely roles of familiarity, field-of-view, and attentional allocation in facilitating its acquisition. The precise nature of survey knowledge from direct and virtual experiences is not the same as that from maps, however, and individuals appear to differ greatly in their abilities to acquire survey knowledge (Hegarty, Montello, Richardson, & Ishikawa, 2000). These too are issues for ongoing and future research.

We restricted our focus in this chapter to the sources of direct experience, maps, and virtual environments. As mentioned above in the section on route and survey knowledge, research on spatial memory has been conducted on a variety of indirect sources besides maps and VEs, including still photographs (Allen, Siegel, & Rosinski, 1978; Hock & Schmelzkopf, 1980; Moar & Carleton, 1982), scale models (Allen et al., 1996; Hunt & Roll, 1987), and videos and movies (Goldin & Thorndyke, 1982; Hooper, 1981). Language in particular is an important source for spatial learning about which researchers are quite interested (Bloom, Peterson, Nadel, & Garrett, 1996). Language generally presents spatial information much more abstractly than do direct experience or virtual environments, and even maps present most *spatial* information fairly iconically.

Finally, it must be stressed that spatial memory from different sources is similar in many ways (for reviews, see McNamara, 1992; Tversky, 1997, 2000). Whatever its source, spatial knowledge stored in memory reveals both random and nonrandom patterns of error and distortion. Any measure of spatial knowledge will reflect error because of simple ignorance about the spatial facts in question. In addition, spatial memory is *schematic*. Shapes become more symmetric and regular over time, remembered as being more like familiar or typical shapes. Turns and angles are remembered as being straighter or more nearly like right angles, an *orthogonality* bias that holds for map-learned and directly experienced spatial knowledge (Sadalla & Montello, 1989; Tversky, 1981), and, we can assume, virtually-acquired knowledge. *Regionalization* effects, the subjective partitioning of environmental knowledge into pieces, characterize all sources too (Allen et al., 1978; Franklin, Henkel, & Zangas, 1995; Gale & Golledge, 1982; Hirtle & Mascolo, 1986). Furthermore, the fact is that spatial memory is often, perhaps usually, based on multiple learning sources (Tversky, 1993). How multiple sources are integrated, or otherwise reconciled, is a critical issue that has been researched only a little (e.g., Ruddle, Payne, & Jones, 1999; Taylor & Tversky, 1992). Taken further, the interaction of different sources may be reflected in ways that experience with one source can change the way knowledge from other sources is encoded and stored. A recent and intriguing case in point is discussed by Uttal (2000), who proposes that training and experience in the use of maps changes the way spatial knowledge acquired from direct experience is conceptualized and stored in memory. Similarly, we can also ask how the increasing use of videogames and more sophisticated virtual environments will change the way people think about and remember space and place. An intriguing possibility is that the "supernatural" capabilities of VEs (instantaneously transporting people, zooming in and out of different scales, etc.) might be used to enhance spatial learning in new ways (Darken & Sibert, 1996; Pausch, Burnette, Brockway, & Weiblen, 1995; Ruddle, Howes, Payne, & Jones, 2000).

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