7

(2005). In P. Shah & A. Miyake (Eds.), The Cambridge Handbook of visuospatial thinking (pp. 257-294). New York: Cambridge University Press.

Navigation

Daniel R. Montello

ABSTRACT

Navigation is coordinated and goal-directed movement through the environment by organisms or intelligent machines. It involves both planning and execution of movements. It may be understood to include the two components of locomotion and wayfinding. Locomotion is body movement coordinated to the local surrounds; wayfinding is planning and decision making coordinated to the distal as well as local surrounds. Several sensory modalities provide information for navigating, and a variety of cognitive systems are involved in processing information from the senses and from memory. Animals update their orientation – their knowledge of location and heading – as they move about. Combinations of landmark-based and dead-reckoning processes are used to update. Humans also use symbolic representations to maintain orientation, including language and cartographic maps. Factors have been identified that make orientation easier in some environments than others. Neuroscience has pointed to the role of certain brain structures in the maintenance of orientation and has uncovered evidence for neurons that fire preferentially in response to an animal's location or heading. Artificial intelligence researchers develop computer models that test theories of navigational cognition or just create competent robots.

INTRODUCTION

Few behavioral problems are more fundamental than getting from here to there. Humans and other mobile animals move about their environments in order to get to places with food, mates, shelter, margaritas, and other resources; they must also avoid threats and dangers such as predation, assault, exposure, and Hanson music blaring from a radio. Furthermore, animals must get from here to there efficiently; going far out of its way is no way to act for a creature with limited time, water, calories, and patience.

This coordinated and goal-directed movement of one's self (one's body) through the environment is *navigation*. Navigation is sometimes a highly technical activity carried out by specialists, or even groups of specialists (see Hutchins, 1995, for an analysis of navigation by teams of navy specialists and their high-tech equipment). However, it is by no means true that only ship captains, pilots, and explorers practice navigation. Virtually every one of us navigates many times a day, with no more technical assistance than the occasional sign or road map, if that. We go to work, we go to shop, we visit friends, we even find our way from the bedroom to the coffeepot each morning. Our main tools for navigating are our repertoires of cognitive abilities – our abilities to perceive, remember, and reason in space and place – and of motor abilities that use cognitive input to produce efficient movement.

In this chapter, I review concepts, theories, and empirical findings on cognitive aspects of navigation. The chapter is multidisciplinary, presenting work by psychologists in various subfields, geographers, linguists, anthropologists, neuroscientists, computer scientists, and others. I focus primarily on human navigation, but as a multidisciplinary topic, researchers study navigation in machines and nonhuman animals as well. Of course a chapter of this length cannot cover all work on navigation, so I provide citations to expanded treatments of particular work where appropriate. The chapter is organized into eight sections. I first discuss component skills in navigation, the proximally coordinated movement part called locomotion and the distally coordinated planning part called wayfinding. The next section discusses geographic orientation, knowing one's location and heading in the environment. Orientation involves reference systems that organize spatial knowledge. As we move, maintaining orientation is known as updating. A variety of sensory systems are involved in orientation, and attentional resources are required to different degrees for different tasks. The third section discusses the use of cartographic maps during navigation. Following that, I discuss characteristics of the external environment that facilitate or impede orientation while navigating. The fifth and sixth sections discuss neuroscience and artificial intelligence approaches, respectively. In conclusion, I consider the effects, both intended and unintended, of new technologies on human navigation. At the end, an annotated list provides suggestions for further reading.

COMPONENTS OF NAVIGATION: LOCOMOTION AND WAYFINDING

I propose that we consider navigation to consist of two components: locomotion and wayfinding. *Locomotion* is the movement of one's body around an environment, coordinated specifically to the local or proximal surrounds – the environment that is directly accessible to our sensory and motor systems at a given moment (or, at most, within a few moments). When we locomote, we solve behavioral problems such as identifying surfaces to stand on, avoiding obstacles and barriers, directing our movement toward perceptible landmarks, and going through openings without bumping into the sides.

There are various modes of locomotion. Unaided by machines, people of different ages (or different states of mind or body) roll, crawl, climb, slither, walk, hop, jog, or run. Aided by machines, there is the usual litany of planes, trains, and automobiles (and then some). Modes of locomotion are important because they determine much about the way we acquire and process information as we locomote. For one, modes differ in the degree to which they are active or passive. Most commonly, this distinction refers to whether the locomoting person controls his or her movement speed and heading. In this sense, active locomotion is self-directed. During self-directed locomotion, people attend to their surrounds and to their own movement, apparently leading to greater environmental learning (Feldman & Acredolo, 1979). They also send efferent commands to their muscles that may provide additional information for learning and orientation. A less common meaning of the active/passive distinction refers to whether the locomoting person is the source of the energy expended to make the body move. In this second sense, active locomotion is self-powered. Unaided by machines, locomotion is usually quite active. Using human-powered machines such as skates, rowboats, and bicycles is somewhat less active, and using machines with engines is particularly passive (the energy required to press a fuel pedal being minimal). Whether locomotion is self-powered is important because one's energy output may provide a heuristic basis for judgments of distance traveled (Montello, 1997); expending energy to move also affects one's arousal and attentional states.

In contrast to locomotion, *wayfinding* is the goal-directed and planned movement of one's body around an environment in an efficient way. Wayfinding requires a place goal, a destination we wish to reach. Frequently, this destination is not in the local surrounds. To a large extent, wayfinding is coordinated distally, beyond the local surrounds directly accessible to our sensory and motor systems at a given moment. Hence memory, stored internally in nervous systems and externally in artifacts such as maps, plays a critical role in wayfinding. When we wayfind, we solve behavioral problems involving explicit planning and decision making – problems such as choosing routes to take, moving toward distal landmarks, creating shortcuts, and scheduling trips and trip sequences.

The great majority of acts of navigation involve both locomotion and wayfinding components to varying degrees; the distinction is less "either/or" than "part-this/part-that." Evidence for the distinction's validity is provided by the simple fact that you can have one without the other. They are generally components of an integrated system of navigation that can be separated only conceptually, but they can sometimes be separated literally. One locomotes without wayfinding when pacing about the maternity ward. A passenger on a bus is locomoting without wayfinding, except when he or she makes decisions as to which bus to board and where to get off. Another example is provided by blind people, some of who can use a long cane or clicking sounds effectively to coordinate movement to the immediate surrounds but may have trouble maintaining orientation to distal goals. Conversely, the present framework includes trip planning at the kitchen table as part of navigation, even though actual movement is only imagined at that point. Effective wayfinding distinct from locomotion is also demonstrated by the Mars Rover autonomous vehicle – it stumbled badly when locomoting relative to nearby features (for example, confusing hills and holes, and falling into holes without any escape) but used its computer maps effectively for wayfinding.

Examples like these help us validate the distinction between locomotion and wayfinding, but they also help us define the semantic boundaries of the term navigation. In the extreme, being carried while sleeping clearly involves no component of wayfinding (on the part of the sleeper), but it also involves so little in the way of locomotion that we may consider it a boundary case for our definition of navigation – probably few researchers, if any, would call it navigation. Similarly, in the prototypical sense, trip planning in advance is only part of the act of navigation, which will also involve steering and acceleration when actually taking the trip. A planned trip that is never taken also provides a boundary case (the other boundary from being carried while asleep) for most researchers' definitions of navigation.

Knowledge Systems in Navigation

The distinction between locomotion and wayfinding has implications for our understanding of the psychology of navigation: "Locomotion is guided both perceptually by current sensory information and cognitively by previously acquired information" (Pick & Palmer, 1986, p. 135). The first form of guidance in this quote is what I am calling locomotion, the second is wayfinding. Locomotion and wayfinding differ greatly in the degree to which they involve perception/action versus memory/planning systems. These systems, in turn, rely differentially on nondeclarative or declarative knowledge and memory (Schacter & Tulving, 1994). *Nondeclarative* knowledge is know-how knowledge, and includes procedural skills and learned motor habits. Many locomotion skills require nondeclarative knowledge. A locomotory act like moving straight to a visible target is probably best understood as coordination of the ambulatory motor system to patterns of optic flow in the environment (Warren, Young, & Lee, 1986) rather than the activation of an internal representation of how the world looks when you move forward. Furthermore, such acts occur without awareness of how they occur – they are impenetrable (Frederickson & Bartlett, 1987). A person's visual-perception system may respond to the velocity or acceleration of changes in the proximal size of an object's image in the visual field (Kerzel, Heiko, & Kim, 1999), but this occurs completely outside of the person's awareness that it is the mechanism by which we avoid collisions. By the same token, impenetrable processes do not respond to conscious knowledge that might be relevant to their operation. That is why people flinch at cinematic depictions of collisions or falls, even when they are fully aware that they are viewing a film and no injury can possibly come to them. Characteristic of impenetrable processes, people are not able to explain how they perform locomotory tasks like walking without stumbling (they may speculate after the fact), if they even realize that it is a complex task worthy of explanation.

In contrast, *declarative* knowledge is know-that knowledge, and includes semantic knowledge of general facts and episodic knowledge of experienced events. It is consciously accessible or explicit knowledge, although it often becomes routinized to the degree that it does not claim much of a person's working-memory resources (more next). So quite unlike the example of walking to a visible target, a wayfinding act such as giving someone verbal directions clearly requires the activation of long-term knowledge representations (the *cognitive map*) into working memory in order to access one's knowledge of place layouts (Lovelace, Hegarty, & Montello, 1999). Except in unusual and perhaps contrived scenarios, there is no sense in which a person can do this simply by "tuning their perceptual system" to the local surrounds (as in Fajen & Warren, 2003), though that is typically an important part of the process. Similarly, wayfinding skills are also typically penetrable. People learn some wayfinding skills through direct instruction, and they can accurately report when they are applying the skills (as in a protocol analysis [Passini, 1992; Pick et al., 1995]).

It must be stressed that neither the declarative/nondeclarative nor the penetrable/impenetrable distinctions map perfectly onto the wayfinding/locomotion distinction. Clear examples that support the validity of the mapping exist, as described earlier, but a few muddy cases and apparent contradictions exist too. Perceiving a surface of support for walking is typically a nondeclarative and impenetrable act, but quicksand appears to provide a surface of support when it does not. Some people use declarative knowledge to recognize quicksand for what it is and make the adaptive, and explicit, decision not to walk over it.

Perhaps the most interesting and important cases where the mapping of declarative/nondeclarative onto wayfinding/locomotion is problematic concern instances where *spatial inferences* are made in relatively immediate surrounds. Take the example of a person pointing directly to the start location after a short vision-restricted walk in a laboratory (e.g., Hazen, Lockman, & Pick, 1978; Loomis et al., 1993). Even though this is generally considered an inference because it involves a spatial judgment along a route not directly traveled, people can perform this inference quickly and easily, without awareness of how they are doing it (Rieser, Guth, & Hill, 1986). The inference appears to depend on the nondeclarative and impenetrable processing of information from nonvisual perception of movement in the local surrounds. Similarly, the desert ant can walk straight back to its nest after a circuitous outbound route (Figure 7.1), an act we would not want to attribute to explicit declarative knowledge. At some point, however, we might expect such journeys will become too long and/or complex for such implicit *path integration*, whether by ant or person (exactly when is not known). Declarative systems (in humans at least) may then be required to form internal or external maps of the journey as wayfinding components to navigation.

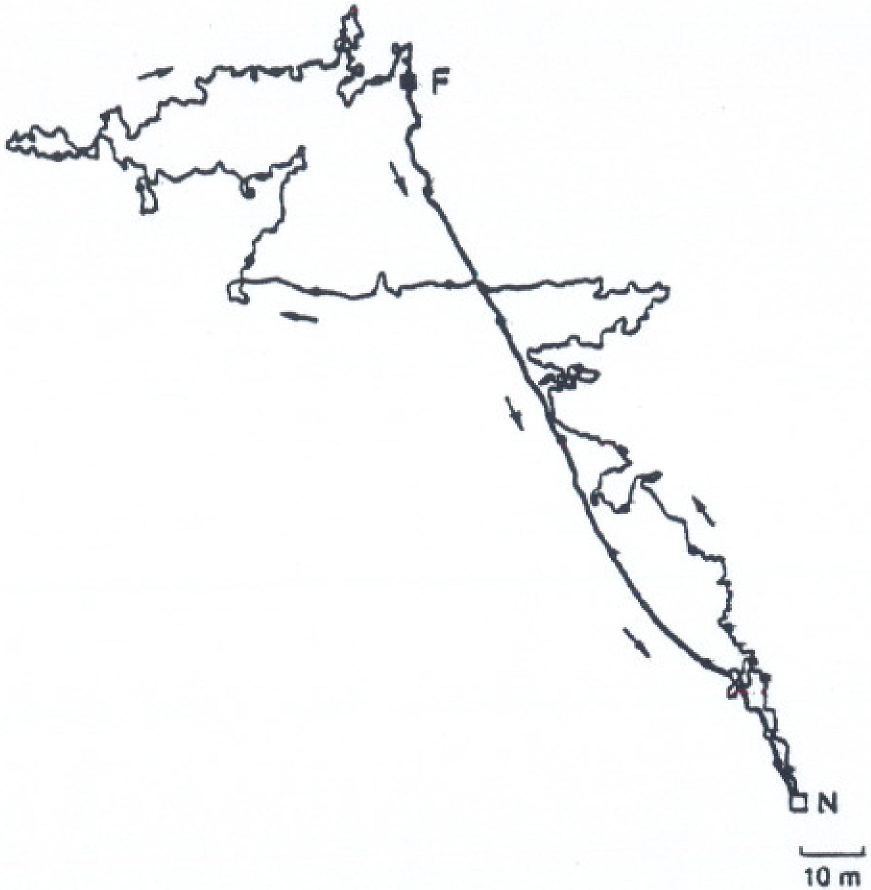

FIGURE 7.1. Direct route taken by desert ant back to its nest after a circuitous outbound trip (from Wehner, 1999).

Metaphorical Navigation

A final comment about the meaning of navigation is in order. The concept of coordinated and goal-directed movement is an extremely flexible and general idea for the expression of meaning in many domains, including many that are not literally spatial. In other words, the concepts of navigation, journeying, getting lost, and so on are very useful metaphors (Johnson, 1987). We speak of "navigating" through a math problem, through a detective story, or through an emotional crisis. Many researchers are studying navigation in computer databases such as the World Wide Web (e.g., Kitchin, 1998). Others are exploring the use of landscape visualizations as ways to metaphorically spatialize nonspatial information (Fabrikant, 2000). However one should be restrained in interpreting metaphors such as "traveling through cyberspace." Like all metaphors, application of the navigation metaphor has limitations. Real navigation involves real places or spaces on the earth, and real movement of the body. The earth's surface is approximately two-dimensional and Euclidean, often overlaid with path networks that modify travel geometry, covered with typical textures and landmark features, structured so as to afford particular types of actions, and so on. The cognitively relevant characteristics of cyberspace in its current form are quite different, although such systems may well become easier to use if redesigned to mimic real space more closely. There is much valuable research to be done extending the mental structures and processes of real navigation, both locomotion and wayfinding, to various forms of metaphorical navigation, but the validity of such an extension should not be uncritically assumed.

GEOGRAPHIC ORIENTATION

Earlier I defined navigation as coordinated and goal-directed movement. Successful navigation means that we reach our goal in an efficient and accident-free manner. To do so requires that as we move, we maintain a sense of where we are relative to our goal, where places and objects we should avoid are located, and so on. That is, we must maintain *orientation* as we move. All behavior (as opposed to uncoordinated body movement) requires some form of orientation: Putting food into your mouth without poking your cheek requires oriented movement. When we consider orientation with respect to our location on the earth's surface, as we do in the case of navigation, we are dealing with *geographic orientation*.

One can be geographically oriented to varying degrees, with respect to various features, and with respect to one or more scales of space or place. People may know what city they are in but not know their location within the city. They may know the bearing to their campsite but not their current location on the trail, other than that it is in the Appalachians; in contrast, they may know the direction along the trail that leads to their destination but not know which compass bearing or how many kilometers away that is. These examples serve to underline the point that a variety of partial knowledge states are associated with being geographically oriented. It rarely if ever makes sense to speak of being completely oriented because there is always some aspect of location or heading that a person does not know precisely. In other words, everyone is potentially *dis*oriented to some degree at all times! Of course, we can usually get to our destinations successfully without being completely oriented. However, in some situations, we fail to maintain adequate orientation, we get lost, and the consequences range from temporary nuisance to death. Behavioral science researchers have begun to apply their science to this problem (see contributions in Hill, 1999a).

Reference Systems

Geographic orientation always involves some mixture of knowing your location, and/or distances and directions to particular places or features.

However we are oriented, it is always relative to something, concrete or abstract. The system for defining orientation is called a *reference system*. A variety of taxonomies for reference systems have been proposed. Hart and Moore (1973) discussed three types: egocentric, fixed, and coordinated. *Egocentric* systems code location relative to one's body. In contrast to egocentric systems, both fixed and coordinated systems are *allocentric*: They code location relative to something outside of one's body, a feature or place in the environment. *Fixed* systems code location relative to a stable landmark, a recognizable and memorable feature. One's home is often used as the origin of a fixed system of reference. *Coordinated* systems code relative to abstract places defined by imaginary coordinate axes laid over large areas. Cardinal directions or latitude-longitude coordinates are examples of coordinated systems. The key distinction between fixed and coordinated systems is that fixed systems are tied to concrete and locally relevant features, natural or built. They are typically useful only over short distances and their continued usefulness depends on their continued existence (or at least continued memory of their existence). Coordinated systems are abstract and function over wide areas, often the entire earth (hence they are *geocentric*). Hart and Moore proposed, following Piaget (Piaget, Inhelder, & Szeminska, 1960), that there is a sequence in child development from egocentric to fixed to coordinated reference systems.

Levinson (1996) recently provided an overview of schemes for classifying reference systems from a variety of behavioral, cognitive, and neuroscience perspectives (e.g., "viewer-centered" versus "object-centered" in vision research [Tarr & Bülthoff, 1998]). As a linguist, however, Levinson's purpose was to explain reference systems in linguistic conceptual systems; absolute distance is apparently not relevant in any language to the closed-class linguistic expressions such as prepositions that reflect conceptual structure (L. Talmy, personal communication, September 22, 2001). So Levinson's typology focuses exclusively on directional reference. As a summary of the various schemes, Levinson proposed a classification of reference systems into relative, intrinsic, and absolute. *Relative* systems are essentially egocentric, as when an object is "to my left." *Intrinsic* systems code direction relative to the asymmetric shape of a feature in the environment; a house has a front door that allows us to speak of being "in front of the house." Finally, *absolute* systems code direction relative to global features that function over large areas or, like the coordinated systems of Hart and Moore, to abstract places defined by imaginary coordinate axes. The ocean provides an example in coastal areas; one may speak of "turning oceanside."

Compared to Hart and Moore's coordinated system, Levinson's absolute system better expresses an aspect of spatial reference that is fundamental to orientation relative to the earth's surface, whether by human or nonhuman animals. Animals orient themselves in terms of their heading[1] relative to the directional orientation of the global surrounds (McNaughton, Knierim, & Wilson, 1995). Whether a magnetic compass, the position of the sun, or the location of the ocean, anything that provides information about the orientation of the global surrounds may be said to provide an *azimuthal reference* (Loomis, Klatzky, Golledge, & Philbeck, 1999). Azimuthal reference captures the idea that the earth's surface is an unmoving and unchanging background for behavior (which at the spatiotemporal scale of animals, it largely is). A critical task for a mobile creature is to understand its movements against this background. Many animal species monitor celestial bodies, winds or currents, or magnetic fields in order to orient themselves to an azimuthal reference (Gallistel, 1990). Humans can and sometimes do monitor celestial bodies for the same reason, and of course, use compasses to monitor magnetism (the doubtful possibility of human magnetoreception is discussed next). Humans and other animals also use terrestrial features to orient to the azimuthal reference, when those terrestrial features are so large that they allow orientation over large portions of the animal's territory. Large bodies of water and large landform features like mountain chains often serve this function, when they are available. Such features might be termed *global landmarks*. And just as it is fundamental for an animal to align its internal cognitive map with the orientation of its surrounds, it is fundamental for a human animal to align its external cartographic map with the orientation of its surrounds – hence the common practice of turning maps while using them (Pick et al., 1995). I discuss this further in the section on using maps to navigate.

Updating During Navigation

Humans and other animals use a combination of two classes of processes to maintain orientation – to update knowledge of their location – as they move about: landmark-based and dead-reckoning processes. *Landmark-based* processes (also called piloting, pilotage, or taking a fix) involve orientation by recognizing features in the world – landmarks. At minimum, landmark-based updating requires that we have an internal or external memory that allows the feature to be recognized. Recognizing a destination landmark in your local surrounds (i.e., in your sensory field) and moving towards it may be termed *beacon-following*, but most of the time there is more to landmark-based updating than just recognizing features in the local surrounds. Usually, we use recognized landmarks in the surrounds to orient ourselves (find our location and heading) on a map that includes the current location and the destination location, when the destination is not in fact visible (or otherwise sensible) from our current location. The map may be internal (cognitive) or external (cartographic). Psychologically, we recognize features in the local surrounds in order to key our current location to our location on a map, which in turn may be "read" to determine a route to our destination. Either way, whether recognized as a destination or as a key to the location of a destination, landmarks almost never function by directly saying "you are here" or "go this way" – visual memory (or that of other modalities) plays a critical role.

In contrast, *dead-reckoning*[2] updating does not involve the recognition of specific external features or landmarks. Instead, it involves keeping track of components of locomotion. Given knowledge of initial location, you can update your orientation by keeping track of the velocity and/or acceleration of your movement for a given period of time. Velocity and acceleration are vector quantities; dead reckoning thus combines knowledge of movement direction with knowledge of the rate of movement. Mathematically, this is equivalent to integrating velocity and/or acceleration with respect to time; hence *path integration* is often used synonymously for dead reckoning[3] (e.g., May & Klatzky, 2000). The psychological mechanism by which dead reckoning occurs is the subject of ongoing research (e.g., Loomis, Klatzky, Golledge, & Philbeck, 1999; McNaughton,

---

[1] Technically, *heading* is your facing direction, *course* is your movement direction, and *bearing* is the direction to a landmark relative to some reference direction (see Gallistel, 1990; Loomis et al., 1999). For a terrestrial animal, heading and course are the same unless the animal is not moving "forward," in the direction it is facing. Heading and course are often quite different for animals (or boats or planes) moving through air or water.

[2] The term *dead reckoning* is usually claimed to derive from *deduced reckoning* (e.g., Gallistel, 1990; Hutchins, 1995). Lewis (1994), however, states that "there is no warrant" for this etymology (note 1, p. 385). The etymology is neither supported nor refuted by the Oxford English Dictionary (2nd ed.). Support for Lewis's contention is provided by Pearsall and Trumble (1996), who include dead reckoning in their entry on the word *dead*, and give as definition 1 for the adverbial use of dead: "absolutely, exactly, completely" (p. 365).

[3] Some writers use the term *dead reckoning* to refer exclusively to velocity-based path integration; *inertial navigation* would refer to acceleration-based path integration (Loomis et al., 1999).

Chen, & Markus, 1991). Researchers have repeatedly shown that humans (e.g., Rieser, 1989) and other animals (e.g., Mittelstaedt & Mittelstaedt, 1980) dead reckon. An amazing example is the desert ant, studied extensively by Wehner (1996, 1999). Figure 7.1 shows the route a desert ant takes to return to its nest after a long and circuitous exploration for food. The research by Wehner and colleagues shows that the ant achieves this direct route by integrating its locomotion over time. By intentionally altering the pattern of polarized light falling upon the ants' eyes, these researchers demonstrated that this integration was based on an azimuthal frame set up by polarized sunlight.

However, by itself, dead reckoning does not provide a complete method of updating and navigation. Dead reckoning requires knowing a start location – it is not useful for establishing orientation relative to places other than that from which recent movement was initiated. Second, dead reckoning suffers from error accumulation. Any error in sensing or processing movement information accumulates over time; except for the unlikely situation where errors coincidentally cancel out, one's orientation becomes increasingly inaccurate over time when based solely on dead reckoning (see Loomis et al., 1993, for data on human dead-reckoning accuracy after walking short paths while blindfolded). Thus, an important research question is how dead reckoning combines with various strategies of landmark recognition to support updating and cognitive-map formation; Loomis et al. (1999) suggest that dead reckoning provides a glue for the formation of cognitive maps.

Sensory Systems for Updating

A variety of sensory and motor systems provide information for updating during locomotion (Howard & Templeton, 1966; Potegal, 1982). Humans recognize landmarks primarily visually, because vision is the most precise channel for spatial and pattern information, particularly at a distance, but landmark recognition may be based on audition, olfaction, radar or satellite signals, and so on. Movement information for dead reckoning is provided proprioceptively (via body senses), notably by the vestibular senses of the inner ear and the kinesthetic senses in the joints and muscles. In theory, motor efference to the limbs (centrally initiated neural commands to the musculature) could provide information for updating, though there is no evidence that it plays this role during whole-body locomotion. Such internally derived signals for dead reckoning are called *idiothetic*. However, external, or *allothetic*, signals play a large role here too. In particular, visual sensing of patterns of texture movement in dynamic optic arrays provides powerful input to our sense of orientation as we move about (Lee & Lishman, 1977), termed *visual kinesthesis* by Gibson (1966); it is important to distinguish this role of visual information from landmark recognition. Audition can contribute to dead reckoning as well (Loomis, Klatzky, Philbeck, & Golledge, 1998). Even magnetic sensing has been offered as a source of information for updating (Baker, 1989). However, this claim has never been reliably supported by direct evidence, and it has proved difficult to replicate in nonhumans (e.g., Kirschvink, Jones, & McFadden, 1985) let alone humans (Gould & Able, 1981).

In nonhuman species, the sensorimotor systems provide information via a variety of modalities and in different ways than that available to human travelers. These fascinating variations, including electrical sensitivity in eels and vision of incredible resolution in raptors, clearly take advantage of the unique ecological niches of different species (see Waterman, 1989). And it should not be forgotten that within the last several centuries, human navigators have made use of a variety of technologies that affect sensorimotor processing during locomotion – everything from lodestone compasses and quadrants to jets and satellites. I discuss new technologies for navigation further in the final section of the chapter.

Attentional Resources During Updating

Whether landmark or dead-reckoning based, updating processes vary in their demands on attentional resources (see Allen & Kirasic, 2003). As discussed earlier, some navigational acts require little attention – they do not use much working-memory capacity. Dead reckoning over relatively short distances is a good example; as cited earlier, Rieser et al. (1986) showed that people could update after short blindfolded walks very accurately and easily, without any awareness of having to think about the task. Other tasks, such as driving between home and work, become automatized over time, leaving attention for the radio, the cell phone, or daydreaming (at least during the majority of the time when active navigational decisions are not being made). Other updating processes, conversely, require working-memory capacity – they are controlled or effortful. Maintaining orientation over more than short distances in unfamiliar environments demands attention – one turns the radio off when nearing a destination in a city never visited before. Considerable attentional resources are needed when giving verbal navigation instructions – directions. Imagining a route and communicating it in words and gestures is generally not automatic, although the museum guard repeatedly pointing the way to the restroom demonstrates that even this can become automatized.

Updating procedures that can potentially be consciously and intentionally applied may be termed *explicit strategies*. Humans often update by using explicit strategies. The application of these strategies, particularly when they are first learned and applied, requires attentional resources. Common examples of strategies are making a point to memorize the number or color of the location of one's car in a parking lot, or simply paying attention. Other strategies include retracing your steps when lost, memorizing the sequence of right and left turns during a journey, verbalizing landmark names out loud, and walking to high points to improve visibility. An important strategy applied by many nautical navigators is *edge following;* when a destination lies along an edge like a coastline, intentionally head to one side of the destination and then follow the edge (hopefully down current) to your destination (Hutchins, 1995). Another method may be called *route* or *direction sampling* (Hill, 1999b). Starting from an established base location, a lost traveler can walk out in various directions for short distances, making sure to keep track of the base. In this way, new information is acquired without risking additional disorientation.

A good example of behavioral-science research on navigational strategies is provided by Cornell, Heth, and Rowat's (1992) research on the *look-back strategy*. Long recommended in wilderness manuals, the look-back strategy involves intentionally stopping, turning around, and memorizing the view behind you while traveling along a route. The strategy is based on the fact that routes often look different in either direction; upon returning from an excursion, the traveler sometimes does not recognize the view in the reverse direction and makes a wrong choice. An especially common version of this navigational error occurs when encountering a fork in the road during the return trip that was not evident during the original trip out (Yogi Berra's advice – that when you come to a fork in the road, you should take it – does not help much). Cornell et al. compared navigational performance by 6-, 12-, and 22-year-old subjects. Subjects took a walk on a college campus with an experimenter who instructed subjects in one of three strategy conditions: no strategy, retrace steps when route feels unfamiliar, or look back and notice view at various points along the walk. Subjects, particularly the 12- and 22-year-olds, stayed on route more and made more correct navigational choices in the look-back condition. This research demonstrated the efficacy of the look-back strategy, and showed it can be explicitly taught and applied effectively by preteens and adults.

The authors proposed that young children lack the metacognitive abilities to properly apply navigational strategies.

In general, wayfinding requires controlled, explicit strategies and working-memory processes when people are in unfamiliar places, including when they are lost. These are more accurately described as reasoning processes than perceptual processes. Passini (1992) provides a framework for understanding cognitive processes during such wayfinding situations. His framework, based on analysis of protocols collected from subjects navigating in public buildings, proposes that wayfinding is composed of three activities: knowledge storage and access (i.e., the cognitive map), decision making for planning actions, and decision execution to turn decisions into behaviors. Such a framework may be applied to understanding how we plan and execute trips, including multistop trips, wherein we organize travel to a series of destinations in an efficient manner (Gärling & Gärling, 1988).

NAVIGATION WITH CARTOGRAPHIC MAPS

Cartographic maps are the quintessential example of external spatial representations of the earth's surface upon which people navigate. There is a large literature on perceptual and cognitive aspects of maps and mapping (see Lloyd, 2000; MacEachren, 1995; Taylor, Chapter 8). There are many types of maps and many tasks for which maps are used. Navigation is but one such task, although among the most important one to most people. And a very important aspect of maps used for navigation is their orientation. To orient a map originally meant to place the east (the Orient) at the top of the map. Putting east at the top seems strange to some people but is no more inappropriate than designing maps with north at the top. The designed orientation of a map, with a particular direction toward the top, is essentially arbitrary, or at least based on rationales that may have no enduring logic. Convention is typically the strongest argument for a particular orientation.

Map orientation is not arbitrary when human psychology is taken into account, however (see also Wickens, Vincow, & Yeh, Chapter 10). Some map orientations make maps harder or easier to understand than others. When using maps to navigate, a large majority of people finds them easiest to use if the top direction of the map is the facing direction (heading) of the viewer. Thus, the "navigator" in the front passenger seat of the car frequently turns the road map as the car turns. This is "forward-up" or "track-up" alignment. If the map is not so oriented, the person navigates

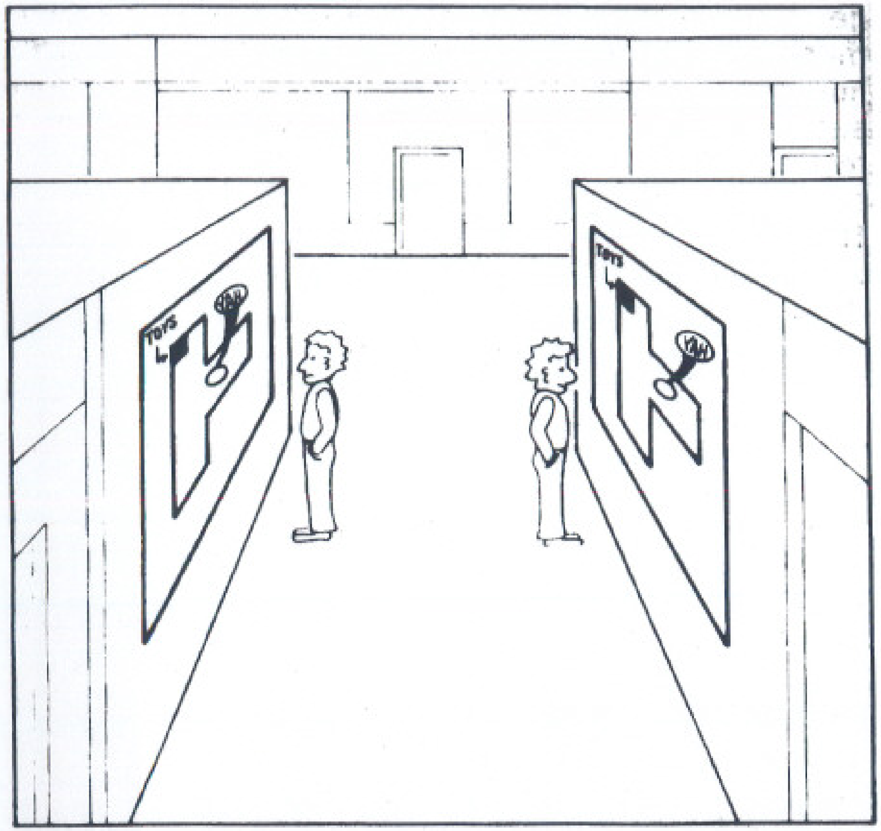

FIGURE 7.2. Mounting the same YAH map in different orientations necessarily produces misaligned maps (from Levine et al., 1984).

less accurately and/or more slowly. For example, a person reading an "inverted" you-are-here (YAH) map, with her facing direction at the bottom of the map, might walk off in the opposite direction from her destination (see Figure 7.2). Such errors or extra time in using improperly oriented navigation maps are called *alignment effects*. Such effects are quite robust, as has been thoroughly documented by Levine and his colleagues (Levine, 1982; Levine, Marchon, & Hanley, 1984) and others (Warren, Rossano, & Wear, 1990). Find a misaligned YAH map and watch people use it – it will not be long before you are convinced of the disorienting power of such maps.

The name for the confusion might more accurately be *mis*alignment effect, because misalignment causes it. Navigation maps require an

alignment or coordination of two directions. One is the direction a person is facing (or traveling) in the local surrounds. The other is the direction on the map toward its top. When these two directions are the same (are aligned), left and right on the map will match left and right in the local surrounds. It may also be easy to treat "forward" in the visual field as "up" on a map because the landscape does in fact "rise" in our visual fields as it stretches out in front of us (Shepard & Hurwitz, 1984). Maps can be misaligned with the surrounds to varying degrees (literally degrees – from 1 to 359 degrees). *Contraligned* maps are 180 degree out of alignment, with their top direction corresponding to straight backwards as the map is viewed.

In order to use a misaligned map properly, one must realize it is misaligned, figure out how it is misaligned, and fix the misalignment. There are a variety of ways a person might accomplish these tasks. For example, one can match the direction of a north arrow on the map with the local direction of north relative to one's heading. Or a person can match feature shapes, such as the outlines of buildings on the map and in the surrounds. On some maps, a YAH arrow can provide information about the proper alignment of the map – if it is pointing other than straight up, the map is misaligned. Once misalignment is recognized, a person can physically or mentally rotate the map or their orientation in the surrounds. When performed mentally, these tasks demand working memory and are easy to apply incorrectly, even for otherwise intelligent people. Levine et al. (1984) found misalignment errors even when the meaning and importance of the YAH arrow was stressed.

The occurrence of alignment effects in maps has practical implications for the design and operation of digital displays in navigation systems for cars or cell phones (Aretz & Wickens, 1992; McGranaghan, Mark, & Gould, 1987; Wickens et al., Chapter 10). Interestingly, a significant minority of people prefers navigation maps such as these to be aligned in a fixed orientation, such as "north-up" (Hickox & Wickens, 1999), probably because of the familiarity of looking at the map in a constant orientation. An interesting but unexplored possibility is that a fixed alignment may better facilitate using maps to acquire knowledge of spatial layout – to form cognitive maps. What differentiates people who prefer a fixed alignment from those who do not is also an important question for research. In any case, these considerations suggest that optimal design for vehicle navigation systems should allow both variable and fixed orientations, controllable by the driver.

For YAH maps, which cannot be picked up and turned, map orientation is clearly one of the most robust and straightforward human-factors issues to consider. However, there are a variety of other map-design issues that apply to navigation maps too, such as legend and symbol design. The degree of schematic abstraction in map design is another relevant issue. All maps are *schematic* to some degree, insofar as their depiction of reality is simplified or generalized; even the most detailed and accurate maps are schematic to some extent. Maps used for navigation need not communicate complete metric information about distances and directions. Particularly when the map is used to navigate on a constrained path network, such as a subway system, most navigators will only want to know the connections among network segments – the quantitative distance between stops may be irrelevant, for instance. In fact, since the London subway map of the 1930s first introduced this style of mapping (Ruggles & Armstrong, 1997), network navigation maps have often been designed in a highly schematic fashion. Such maps are sometimes called *topological* maps because they intend to communicate topological information such as line connectivity but not metric information such as distance. All pictures in our world are metric, however; they depict distances and directions even when that information is meant to be ignored. So does the navigator ignore the potentially misleading metric information? Evidence suggests that some navigators do overinterpret schematic map displays (Berendt, Rauh, & Barkowsky, 1998), possibly leading to the acquisition of distorted spatial knowledge. More research is needed on the effects of maps on wayfinding and spatial learning, and what information navigators actually need from maps.

THE PHYSICAL ENVIRONMENT IN NAVIGATION

Navigation occurs in physical environments. The visual and structural characteristics of those environments make it easier or harder to perform various navigation tasks. Flying through the air is different than walking over ground or sailing on the sea. Walking over prairie is different than walking over mountains or crawling through caves. With respect to cognition, these differences are trivially true for locomotion. Yes, it is easier to walk on firm ground than on muddy ground. Much more interesting are the ways that different environments afford different information for wayfinding tasks such as staying oriented to distant goals while moving about. Different information allows different wayfinding strategies, and it makes the strategies easier or harder to apply effectively.

There are many ways to conceptualize physical environments that might help us understand their role in navigation. Certainly, the distinctions suggested earlier are important: air versus water versus ground, flat ground versus mountainous ground, above ground versus underground. One distinction that encompasses a variety of relevant characteristics is that between built and natural environments. *Built* environments are created by humans; *natural* environments are created relatively freely of human agency. There are many intermediate cases, of course, and the very concept of "natural" is extremely complex and imperfect (e.g., Proctor, 1998). Nevertheless some useful generalizations can be made. Built environments have more regular patterns, like straight lines and right angles (although both are found in natural environments). In many built environments, for example, the road network consists entirely of rectilinear grids or symmetric radial patterns. Few buildings have corridor structures anywhere near the complexity of the average cave structure. The appearance of built and natural environments tends to be rather different, although not in any way that is easy to characterize generally. The presence of more curved, irregular, and asymmetric shapes in natural environments gives them a greater visual complexity in one sense, but at some point, this creates visual homogeneity as compared to the more minimalist character of built environments. Structures in built environments can vary capriciously in terms of color and height in ways that violate "natural logic"; in contrast, and unfortunately for the navigator, built environments sometimes capriciously lack variation. With respect to navigation, one of the most important differences between built and natural environments is that the first often come equipped with a semiotic labeling system that aids orientation – signs telling navigators where they are and where to go.

Weisman (1981) offers an interesting analysis of physical environmental characteristics that affect orientation during navigation (see also Gärling, Böök, & Lindberg, 1986). Although intended to apply to designed (i.e., built) environments, his factors apply nearly as well to natural environments. The four factors are: (1) differentiation, (2) visual access, (3) complexity of spatial layout, and (4) signage. *Differentiation* is the degree to which different parts of an environment look the same or different. Environments may be differentiated with respect to size, shape, color, architectural style, and so on. Generally, more differentiated environments are easier to wayfind in because the differentiated parts are more distinct and memorable – differentiation creates better landmarks (Appleyard, 1969; Lynch, 1960); at some point, however, differentiation could be taken to a disordered extreme that would be disorienting. Gladwin (1970) tells the fascinating story of the navigators of the Pulawat Islands of Micronesia (other South and West Pacific peoples have similar traditions). They are able to pick up a great deal of useful information from their watery environment, which is rich in differentiation to those trained to perceive it. This information allows technologically unaided boat trips of a hundred miles or more over open ocean, and includes air and water color, wave and swell patterns, sun and star patterns, and bird species identification.

The second factor of *visual access* (or *visibility*) is the degree to which different parts of an environment can be seen from various viewpoints. From which locations can navigators see their start locations, their destinations, and various landmarks along the way? Is the pattern of the environment, including its path structure, visible from a single viewpoint? Greater visual access obviously makes orientation easier. A promising approach to the systematic analysis of visual access is provided by *isovist theory* (Benedikt & Burnham, 1985); the *isovist* is the collected spatial extent of all views, or vistas, from a single location within an environment. A square room has a large and symmetric isovist (from its center) compared to that of a room of the same area broken up by dividing walls. And within the same environment, the isovist differs from different locations (Figure 7.3). Isovist theory, conceived by Hardy (1967) and named by Tandy (1967), was inspired by a planning concern for the visual appearance of the landscape and an appreciation of Gibson's (1950) ideas about the visual perception of texture gradients in the environment. The theory proposes that characteristics of isovists, such as size or shape, will help explain different psychological responses, such as ease of orientation and verbal description, in different places. In the disciplines of cartography and surveying, isovist analysis is known as *viewshed analysis* (see Llobera, 2003).

Weisman's (1981) third factor, *complexity of spatial layout*, is a heterogeneous notion that is difficult to express in formal terms. Exactly what constitutes a complex layout, in the sense that it makes orientation more confusing, is a question for research. A more articulated space, broken up into more different parts, is generally more complex, although the way the different parts are organized is critical. It is clear that certain patterns of path[4] networks are more or less complex in this sense; for example, oblique turns are more disorienting than orthogonal turns (Montello, 1991). What is difficult here, though, is that the overall shape or gestalt of a path layout can determine whether a particular element is disorienting (Weisman [1981] in fact focused on the "good form" of a layout's overall configuration). A curved street is understood better when it fits within a radial

---

[4] I distinguish *paths*, linear physical features in the world upon which travel occurs (roads, trails), from *routes*, linear patterns of movement by a traveler. Routes of travel may occur on paths or across areas that contain no paths, like open fields.

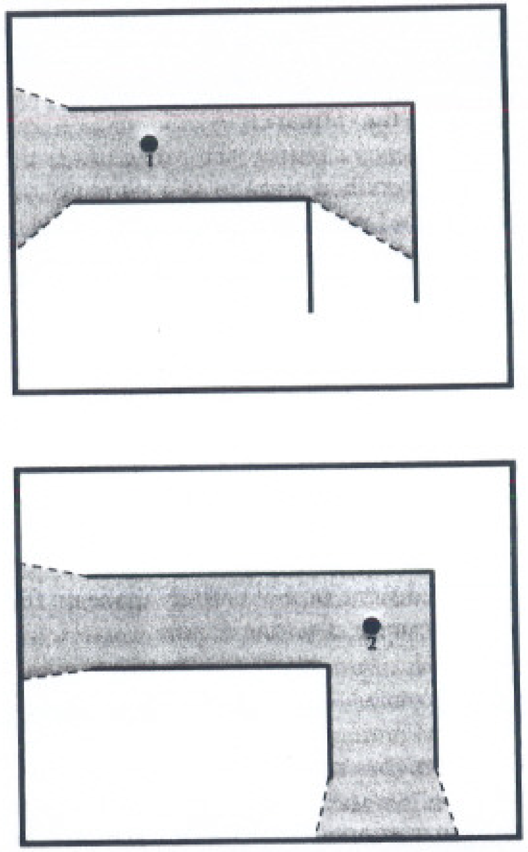

FIGURE 7.3. Two-dimensional isovists from two different locations (1 and 2) within the same hallway.

network pattern, as long as that radial pattern is in fact apprehended. A grid pattern may be disorienting if its axes do not run north-south and east-west – at least for those navigators who incorporate cardinal directions in their wayfinding. Layouts may be said to vary in their closeness to a good form – wayfinding is easier when the layout has an overall pattern that can be apprehended as a single simple shape. A square is easier than a rhombus; a circle is easier than a lopsided oval. People apparently try to understand layouts as good forms, and when the layout does not have such a form, disorientation can result (Tversky, 1992). A classic example is reported by Lynch (1960), who found that people were confused by the Boston Commons because they tended to assume it is a square when it is actually an irregular pentagon. I have heard that the Pentagon, headquarters of the U.S. military, was intentionally designed as a five-sided shape to disorient intruders. If they really wanted to disorient, they could have designed it with five sides but called it the "Square."

Finally, Weisman (1981) listed *signage* as a fourth factor that affects the legibility of environments. Earlier, I described signage as a semiotic system that aids orientation. The design and placement of signs and maps in the environment clearly affects orientation (Arthur & Passini, 1992). Unfortunately, as my discussion of misaligned YAH maps makes clear, signs can *dis*orient too. Effective signage must be legible from a distance, must be clear and simple in design, must have enough but not too much information, and must be placed where the navigator needs information (at decision points, for instance). The challenge of designing comprehendible iconic symbols for signs is especially great; does an arrow pointing straight up mean go forward or go up one floor? With signs, as with layout complexity, many contextual factors influence effectiveness. A perfectly clear sign may be confusing if it is placed in a sea of competing visual clutter. And even the best designed and placed signs cannot entirely make up for poor characteristics of the other three physical-setting factors.

NEUROSCIENCE OF NAVIGATION

The neuroscience of navigation, in humans and nonhumans, is a growing area of research (Paillard, 1991). This research attempts to answer questions such as how spatial information relevant to navigation is encoded in nervous systems, which brain areas process navigation information, how sensory information for navigation is integrated in the nervous system, and how particular injuries or organic syndromes produce particular deficits in navigational behavior.

One of the earliest findings in this area concerned the involvement of the *hippocampus* in spatial learning during navigation. The hippocampus is a brain structure located within the temporal lobe, surrounded by the lateral ventricle, and connected to subcortical nuclei via the fornix and to the neocortex via the parahippocampal region (Eichenbaum, 1999). These anatomical connections point to the hippocampus as a final convergence location for outputs from many areas of the cerebral cortex, and a source of many divergent outputs to cortical and subcortical areas. These anatomical connections reflect the apparent role of the hippocampus as a major organizer of memory representations. Observations of rats with hippocampal lesions have revealed deficits in the ability to learn maze layouts (Mizumori, 1994; O'Keefe & Nadel, 1978). Recordings of the activity of single brain cells in the hippocampi of rats as they navigate in mazes have revealed the existence of neurons that preferentially fire when the rat is in a particular location (O'Keefe, 1976). These *place cells* fire independently of the rat's heading, and even when stimulus features within the maze are modified, as long as extramaze features exist to define a location (O'Keefe & Conway, 1979). The extramaze cues are typically visually based, but can also be nonvisual. The location where the place cells fire is known as the *place field* (Mizumori, 1994).

However, spatial encoding is not unique to hippocampus cells; heading is coded by *head-direction cells* in structures with afferent and efferent connections to the hippocampus, and movement velocity appears to be coded in connected structures as well (Mizumori, 1994). Furthermore, the job of the hippocampus is not exclusively to process spatial information. It has long been known that hippocampal lesions in humans cause forms of amnesia for nonspatial information, and that nonhumans show some hippocampal-caused deficits in nonspatial learning (Eichenbaum, 1999). It is now generally recognized that the hippocampus serves to integrate information into flexible multimodal representations, organizing and encoding experience in relation to its spatiotemporal context. In humans, hippocampus lesions cause deficits in the ability to store episodic memories (Eichenbaum, 1999; Maguire, Burgess, Donnett, Frackowiak, Frith, & O'Keefe, 1998). Of course, this is not inconsistent with the idea that the hippocampus plays a central role in some aspects of spatial cognition; it just indicates that spatial cognition plays a central role in cognition more generally.

Findings of selective deficits and single-cell activity have led to several models of the role of the hippocampus and connected structures in spatial information processing during navigation and place learning. O'Keefe and Nadel (1978) proposed that the hippocampus is the site where an allocentric cognitive map of the environment is constructed and stored. More recently, McNaughton and his colleagues (e.g., McNaughton, Chen, & Markus, 1991; McNaughton et al., 1995) have developed and tested computational models of cortical-hippocampal interaction in which the hippocampus retains views of locations and their interrelations derived from movement. In other words, they have formally developed the idea that dead reckoning serves as a glue to integrate sensory experiences into memory representations of spatial layout, based on the maintenance of an azimuthal frame relating an organism's heading to the orientation of the external surrounds (see also Mizumori, 1994; Poucet, 1993).

TABLE 7.1. *Taxonomy of Topographic Disorientation Syndromes (from Aguirre & D'Esposito, 1999)*

Disorder	Lesion Site	Proposed Impairment
Egocentric disorientation	Posterior parietal	Location of objects relative to self
Heading disorientation	Posterior cingulate	Heading relative to external environment
Landmark agnosia	Lingual gyrus	Appearance of salient environmental features
Anterograde disorientation	Parahippocampus	Creation of new representations of environments

Clinical studies of organic brain syndromes and injuries have shed light on the neuroscience of navigation in humans (reviewed by Aguirre & D'Esposito, 1999). Specific impairments in some aspect of navigational ability following localized brain injuries are known as *topographical disorientation*. Topographical disorientation refers particularly to physiologically caused deficits in wayfinding rather than locomotion: knowing which way to head to get to a nonvisible landmark rather than being able to walk straight to a beacon in the visual field, for example. Aguirre and D'Esposito (1999) list four topographical disorientation syndromes that have been hypothesized to exist based on documentation of one or more clinical cases. Reprinted in modified form in Table 7.1, their taxonomy includes egocentric disorientation, heading disorientation, landmark agnosia, and anterograde disorientation. The evidence is clearest for landmark agnosia, an inability to represent the appearance of salient features in the environment, caused by lesions to the lingual gyrus. A couple of notable conclusions from this work is that the role of the hippocampus in spatial learning is not as clear in humans as in nonhumans, and that many nonhippocampal structures play an important role in various aspects of spatial learning and navigation.

Finally, brain imaging of awake and normally functioning humans is beginning to increase our understanding of the neuroscience of navigation. Maguire et al. (1998), for example, reported positron emission tomography (PET) scans of humans while they navigated in a desktop virtual town. The scans suggested different roles for right and left hemisphere brain structures. Activity in both the right hippocampus and right inferior parietal cortex was associated with navigating to nonvisible landmarks. The authors interpreted this as consistent with the hippocampus's role in forming allocentric maps and the inferior parietal cortex's role in egocentric orientation. The left frontal cortex was active during responses to enforced detours, suggesting to the authors its role in planning and decision making, which are typical wayfinding acts, during navigation. Brain imaging techniques hold great promise for increasing our understanding of the neural substrates of cognition and behavior, including navigation. At this time, however, they are greatly limited by their restriction to use with nonmoving subjects. The relationship between navigation in real and virtual environments has yet to be conclusively established.

ARTIFICIAL INTELLIGENCE APPROACHES

An important body of cognitive work on navigation has been carried out by researchers in the field of artificial intelligence (AI). It is critical to keep in mind that AI researchers have varied goals. Some want to use computer simulations to test theories about how humans or other animals navigate. Others want to make a computer do something, regardless of whether it does it like an animal does it. A few researchers with this latter goal nonetheless believe they can learn something useful from looking at existing examples of successful navigating entities. They just don't worry about designing all aspects of their intelligent systems in realistic, animalistic, ways. Many researchers with the goal of making a navigating computer, a *robot*, are not concerned in the least with how animals do it. In such cases, the researcher only wants to make a system that works, regardless of whether it works like some animal. Thus, robots are frequently designed that take advantage of large memories and processing speeds, and powerful sensory-motor systems, that are quite unrealistic for an animal. No animal has a laser range-finder, for example.

AI research on navigation supports the value of distinguishing locomotion from wayfinding processes, as was mentioned earlier. Roboticists have typically focused on locomotion rather than wayfinding – their robots move down hallways or follow road patterns but often do not plan routes or give directions (e.g., Aloimonos, 1996). A telling example is provided by Brooks (e.g., 1991). For some time, he and his colleagues built robots that could locomote without internal representations of the external environment. He in fact attempted to make the scientific case that navigation did not require a cognitive map, but his evidence consisted of machines that could locomote (to an extent) but could not wayfind. In contrast, some AI workers other than roboticists have used computational models to test theories about how animals, including humans, navigate and learn spatial information (McDermott & Davis, 1984; Yeap, 1988). These

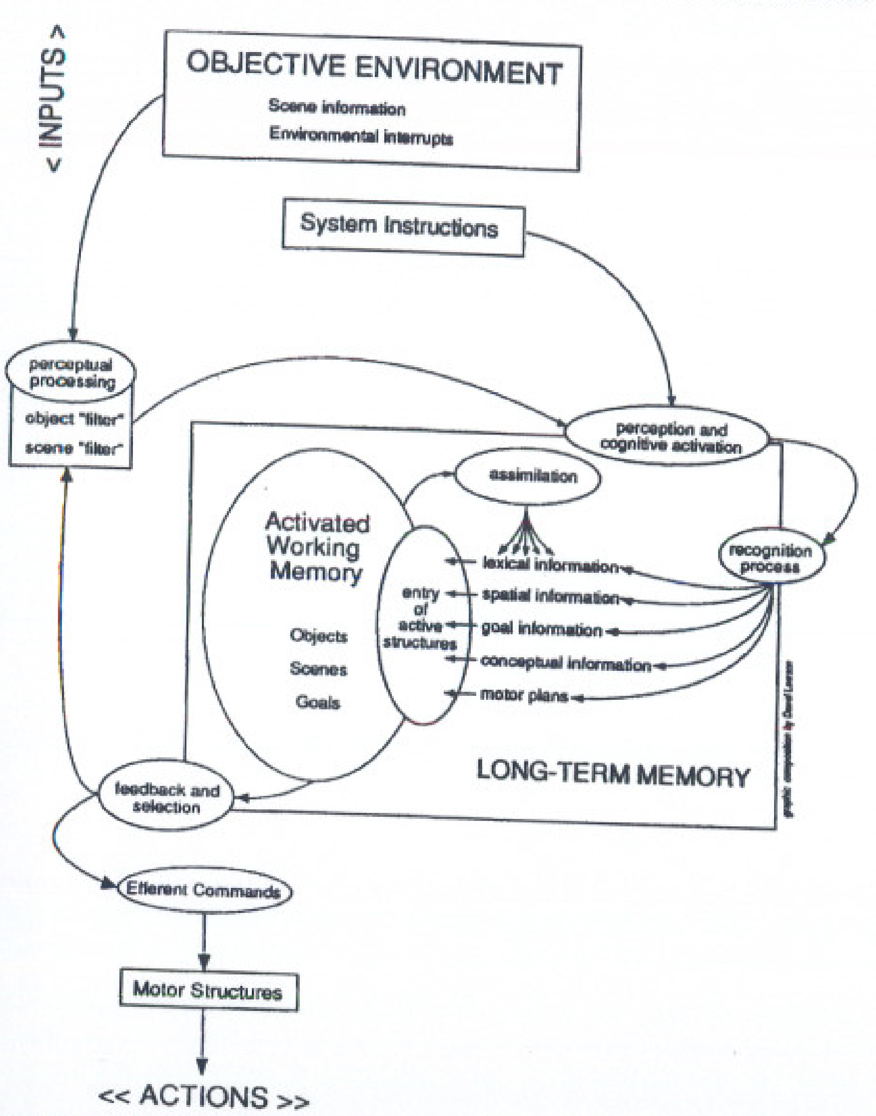

FIGURE 7.4. The NAVIGATOR model by Gopal et al. (1989), a computational-process model of navigation and spatial learning.

computational-process modelers typically focus on simulating wayfinding rather than locomotion – their models "reason" about choosing routes or heading in the direction of a goal, but they do not actually "go" anywhere. A good example is the NAVIGATOR model by Gopal, Klatzky, and Smith (1989), shown in Figure 7.4.

A complete computational simulation of animal navigation would clearly perform both locomotion and wayfinding tasks. Fortunately, the distinction between locomoting robots and wayfinding programs has been breaking down, in practice (M. E. Jefferies & W.-K. Yeap, personal communication, December 16, 1999). That is, researchers are more likely to create AI simulations that perform both locomotion and wayfinding.

The influential work of Kuipers and his colleagues is a case in point. He has done some of the earliest AI work on navigation that incorporates ideas about human navigation. It is worthwhile to consider his work in some detail, as it is the most comprehensive research program in AI that utilizes and develops organismic theories of navigation, and because it touches on nearly all of the issues that confront AI modelers working on navigation. Kuiper's TOUR model (1978) was a computational-process model of navigation and spatial learning. It has recently been clarified and extended more directly to locomotion tasks in his "Spatial Semantic Hierarchy" (SSH) (Kuipers, 2000). The SSH posits four distinct and somewhat separate representations or levels for knowledge of large-scale space derived from and supporting navigation; the four are simultaneously active in the cognitive map, according to Kuipers. The four levels are:

(1) *Control level* – This is grounded in sensorimotor interaction with the environment, and is best modeled in terms of partial differential equations that express control laws specifying continuous relations between sensory inputs and motor outputs.
(2) *Causal level* – This is egocentric like the control level, but discrete, consisting of *views* defined by sensory experiences and *actions* for moving from one view to the next. The views and actions are associated as schemas and are best modeled using first-order logic.
(3) *Topological level* – This includes a representation of the external world, but only qualitatively, including places, paths, regions and their connectivity, order, and containment. First-order logic is appropriate here too.
(4) *Metrical level* – This representation of the external world includes distance, direction, and shape, organized in a global allocentric reference system. This is modeled best by statistical estimation theory, such as Bayesian modeling.

Kuipers (2000) presents some evidence for the SSH from partial implementations on simulated and actual robots.

Other AI researchers have modeled navigation and spatial learning (Chown, Kaplan, & Kortenkamp, 1995; Yoshino, 1991). All of these

AI models share certain concerns or ideas. First, all posit multiple representations of space varying in the degree to which they depend on each other; as in Kuipers's SSH, some models suggest that different computational approaches or *ontologies* are most appropriate for different types of representations and different navigational tasks. All models include bottom-up processing from sensorimotor information, although as I suggest earlier, the models vary in the degree to which they explicitly model these bottom-up sensorimotor processes (they have to be modeled in a robot but may be assumed in a nonmoving program). All models posit the importance of landmarks, which are features or views in the space that are noticed as distinctive, remembered, and used to help organize spatial knowledge. In some way, all models concern themselves with the derivation of allocentric 3-D (or 2.5-D) maps from egocentric 2-D views of the world, including in some cases a distinction between local and global allocentric representations. Different models vary in the degree to which they posit metric knowledge of distances and directions in addition to topological knowledge; the metric knowledge is frequently modeled as being qualitative or fuzzy. The models all recognize the problem of integrating spatial information encoded in multiple systems of reference, and they generally employ some type of hierarchical representation structure such as graph trees to encode hierarchical spatial and thematic relations in the world. Taken together, these various properties of AI simulation models point to what may be their greatest contribution to the multidisciplinary understanding of navigation as a cognitive problem: The existence of partial, imprecise, and distorted knowledge enables the digital entity to deal robustly with uncertain and faulty information during navigational learning and problem solving.

SUMMARY AND CONCLUSIONS: THE FUTURE OF NAVIGATION

Navigation, coordinated and goal-directed movement through the environment, is a ubiquitous task performed by mobile animals. In prototypical form, it involves both planning and execution of movements. To navigate successfully, animals perform perceptual and cognitive operations on information from the body, from the environment, and, in the case of human beings, from symbolic sources such as maps, signs, or words. To understand navigation as a cognitive task, I organize it into the two components of locomotion and wayfinding. Locomotion refers to body movement coordinated to the local surrounds, and includes identifying surfaces of support, avoiding barriers, and other activities. Wayfinding refers to the planning and decision-making activities that allow goal-directed locomotion coordinated to the distal as well as local surrounds. Such activities include orienting to currently nonperceptible goals, giving verbal directions, and other activities.

Perhaps vision contributes the most navigational information under normal circumstances, at least for human beings, but a variety of other modalities such as vestibular sensing also play a part. Several other distinctions among psychological systems help us understand navigational behavior and information processing. Both perception/action and memory/planning systems are involved, to different degrees in different navigational tasks. Both declarative and nondeclarative knowledge processes operate in navigational tasks as well. Locomotion tasks are more often cognitively impenetrable, and tend to demand less working-memory capacity, as compared to many wayfinding tasks. Penetrable wayfinding strategies can be intentionally acquired and applied.

Animals maintain a sense of location – they geographically orient. Animals can be oriented to varying degrees, with respect to various features, and with respect to different scales of space. Orientation requires a system of reference for defining location. A variety of reference systems are used by animals, particularly humans, but the system that orients the animal to the orientation of its global surrounds, an azimuthal system, is particularly fundamental to geographic orientation. Animals update their sense of orientation as they move about. To do this, they use a combination of landmark-based and dead-reckoning processes. Landmark-based processes involve the recognition of external features or scenes. Dead-reckoning processes involve attention to information about body movement (speed, direction) without recognition of specific landmarks.

People frequently use cartographic maps to navigate. The orientation of navigation maps has been shown to strongly affect how easily they are used. A forward-up alignment is typically, but not always, easiest to use. The difficulty of using maps that are misoriented relative to the surrounds is called an alignment effect. To use misaligned maps, the navigator must recognize they are misaligned and compensate appropriately. A variety of additional issues have implications for the design of cartographic displays used to navigate.

The structure and appearance of physical environments affects the ease of orienting within them. The distinction between built and natural environments helps account for some of the effects. In general, environments are easier to orient within when they have high differentiation, high visual access, and low complexity of spatial layout. The latter factor has an especially potent effect on orientation, although in ways that are often difficult to characterize a priori. Layout complexity depends in part on the situational context, and is a function of both local and more global geometric relations. Unique to environments that have at least partially been created by people, the quality of signage also affects orientation.

There is a growing body of literature on the neuroscience of navigation. This research includes studies of single-cell recordings of nonhumans (especially rats) performing navigation tasks, lesion studies in nonhumans, studies of organic syndromes in clinical patients that affect navigation in different ways (called topographical disorientation in this literature), and brain-imaging studies of normal adults performing navigation in simulated environments.

Finally, behavioral and computational scientists have investigated navigation as a problem for artificial intelligence. Some AI researchers use computational models to test theories of navigation by animals; others just want to make robots that work. Among the first group, several issues are recurring concerns: the existence of multiple representations of space, the relative contributions of bottom-up and top-down processes, the role of landmarks, the derivation of allocentric maps from egocentric views of the world, the relative roles of metric and nonmetric knowledge, and the application of multiple reference systems and hierarchical organization. Attention to these concerns allows AI models to address the robustness of navigation in the face of uncertain information.

There are important topic areas within the theme of navigation that could not be covered in any detail in this chapter, given its space limitations. There is a great deal of research on navigation by nonhuman animals (see Schöne, 1984; Wehner, Lehrer, & Harvey, 1996) that has only been touched on here. Focusing just on human navigation, questions about how and why individuals and the two sexes differ in their navigation styles and abilities is covered in Hegarty and Waller (Chapter 4), and Halpern and Collaer (Chapter 5), respectively. The development of navigational cognition throughout the life span, and ways that it differs as a function of age, are discussed in Hegarty and Waller (Chapter 4) and Newcombe and Learmonth (Chapter 6). Spatial knowledge acquisition (learning the cognitive map) often occurs during navigation and, as discussed in this chapter, produces knowledge that provides a basis for wayfinding behaviors. There is a great deal of research literature on spatial learning (Golledge, 1987; Montello, 1998; Thorndyke & Hayes-Roth, 1982) that is not reviewed in this chapter. And a complete discussion of higher-level cognition in navigation would include research on the verbal communication of navigational information (Allen, 1997). Finally, navigation in virtual environments is currently of great research interest (Ruddle, Payne, & Jones, 1997); this growing topic is considered in Wickens, Vincow, and Yeh (Chapter 10).

The advent of virtual-environments technology is but one example of the technological developments that are changing human navigation, including the cognitive processes that are part of navigation. Over the centuries, humans have developed a variety of new technologies to aid navigation. Recent developments will have effects on navigation, especially wayfinding, that are nothing short of revolutionary. A key technology is the satellite system for locating oneself on the earth's surface, known as the *Global Positioning System* (GPS). Inexpensive and portable access to this system is now available for automobile navigation systems, cell phones, and other types of personal navigation assistants. Particularly with recent improvements in the resolution of the satellite signal made available to civilians, people can accurately locate themselves most anywhere on the earth to within meters. Other navigational technologies include auditory signage for the visually impaired, and radio transmitters for tracking children or those suffering from Alzheimer's disease.

These technologies will clearly have a profound impact on how people stay oriented and make navigational decisions. Especially powerful is the way that digital information can be flexibly tailored to a specific situation in a way that rarely happened in the predigital age. Many, many hours of disorientation will be avoided; fear, anxiety, and frustration will be reduced; lives will be saved. However, one should not accept the advertisement hype that you will "never get lost again!" People will always get lost, and in some ways, they will get lost worse because of new technologies. Satellite systems fail sometimes, and they can be distorted or blocked by local obstructions. Electronic machines lose power or just plain break. Possessing the technology is going to lead to a false sense of security, which in turn will lead to an unprecedented lack of preparation and of practice in traditional navigation. Hikers will go out without appropriate prior planning or without good old paper maps or compasses. Who is going to bother with the look-back strategy when they can rely on a hand held satellite receiver tapping into millions of dollars of the latest technology? There are already documented cases of wilderness disorientation because of cell phone failure (E. H. Cornell & C. D. Heth, personal communications, July, 1999).

Even given accurately functioning technology, people will still be able to lose their way. Possessing a map or verbal directions, no matter how complete and accurate, has never guaranteed protection from disorientation, and it never will. Being provided with latitude-longitude coordinates certainly won't solve the problem. Making the map or the directions digital doesn't matter, and will in fact create more problems while the bugs in the databases and algorithms get worked out. There are a host of important and interesting new research questions that are created by new navigational technologies. How should navigational interfaces be designed (Streeter, Vitello, & Wonsiewicz, 1985), and how should people be trained to use them? However, many research questions will remain the same. New technologies do not obviate the need to decide what information should be given to navigators, and how it should be communicated. As long as people have to decide where to go and how to get there, navigation will remain one of the fundamental behavioral problems for human cognition.

ACKNOWLEDGMENTS

I thank the editors and three reviewers for comments that have increased the chapter's clarity. John Reiser suggested the interesting examples of blind navigation and the Mars Rover. An overview chapter such as this is an appropriate place to thank members of the UCSB spatial cognition community: Reg Golledge, Mary Hegarty, Jack Loomis, Helen Couclelis, Sara Fabrikant, and several graduate students and post-docs. I also thank the many contributions of mentors and colleagues at other institutions over the years. They have provided an intellectual milieu critical for the creation and refinement of ideas, but of course the poor ideas are all mine.

Suggestions for Further Reading

An insightful review and interpretation of literature on learning, particularly spatial learning in nonhumans, including behavioral, computational, and neuroscience work. Includes useful overview of basic concepts of navigation and spatial knowledge:
Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: The MIT Press.

State-of-the-art edited collection by behavioral scientists working with humans and nonhumans. Provides overview of both wayfinding and locomotion:
Golledge, R. G. (Editor). (1999). *Wayfinding behavior: Cognitive mapping and other spatial processes*. Baltimore, MD: Johns Hopkins Press.

Explains situated cognition in an engaging manner, using a detailed explication of social and technical factors in nautical navigation as a demonstration case:
Hutchins, E. (1995). *Cognition in the wild*. Cambridge, MA: The MIT Press.

Comprehensive discussion of traditional navigation techniques by various peoples of the South and West Pacific islands. Both psychological and material issues considered:
Lewis, D. (1994). *We, the navigators: The ancient art of landfinding in the Pacific*. (2nd ed.). Honolulu: University of Hawaii Press.

Classic edited collection of human behavioral-science research on spatial cognition, development, and navigation:
Pick, H. L., & Acredolo, L. (1983). *Spatial orientation: Theory, research, and application*. New York: Plenum.

Edited special issue with many contributions by top researchers of nonhuman animal navigation. Organized around the theme that different mechanisms and structures operate at different scales of navigation:
Wehner, R., Lehrer, M., & Harvey, W. R. (Editors). (1996). Navigation: Migration and homing [Special issue]. *The Journal of Experimental Biology, 199*(1).

References

Aguirre, G. K., & D'Esposito, M. (1999). Topographical disorientation: A synthesis and taxonomy. *Brain, 122*, 1613–1628.

Allen, G. L. (1997). From knowledge to words to wayfinding: Issues in the production and comprehension of route directions. In S. C. Hirtle & A. U. Frank (Eds.), *Spatial information theory: A theoretical basis for GIS* (pp. 363–372). Berlin: Springer.

Allen, G. L., & Kirasic, K. C. (2003). Visual attention during route learning: A look at selection and engagement. In W. Kuhn, M. Worboys, & S. Timpf (Eds.), *Spatial information theory: Foundations of geographic information science* (pp. 390–398). Berlin: Springer.

Aloimonos, Y. (1996). *Visual navigation: From biological systems to unmanned ground vehicles*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Appleyard, D. (1969). Why buildings are known. *Environment and Behavior, 1*, 131–156.

Aretz, A. J., & Wickens, C. D. (1992). The mental rotation of map displays. *Human Performance, 5*, 303–328.

Arthur, P., & Passini, R. (1992). *Wayfinding: People, signs, and architecture*. Toronto: McGraw-Hill Ryerson.

Baker, R. R. (1989). *Human navigation and magnetoreception*. Manchester: Manchester University Press.

Benedikt, M., & Burnham, C. A. (1985). Perceiving architectural space: From optic arrays to Isovists. In W. H. Warren & R. E. Shaw (Eds.), *Persistence and change: Proceedings of the First International Conference on Event Perception* (pp. 103–114). Hillsdale, NJ: Lawrence Erlbaum Associates.

Berendt, B., Rauh, R., & Barkowsky, T. (1998). Spatial thinking with geographic maps: An empirical study. In H. Czap, H. P. Ohly, & S. Pribbenow (Eds.), *Herausforderungen an die Wissensorganisation: Visualisierung, multimediale Dokumente, Internetstrukturen* (pp. 63–73). Würzburg: Ergon.

Brooks, R. A. (1991). Intelligence without representation. *Artificial Intelligence, 47*, 139–159.

Chown, E., Kaplan, S., & Kortenkamp, D. (1995). Prototypes, location, and associative networks (PLAN): Toward a unified theory of cognitive mapping. *Cognitive Science, 19*, 1–51.

Cornell, E. H., Heth, C. D., & Rowat, W. L. (1992). Wayfinding by children and adults: Response to instructions to use look-back and retrace strategies. *Developmental Psychology, 28*, 328–336.

Eichenbaum, H. (1999). Hippocampus. In R. Wilson & F. Keil (Eds.), *The MIT encyclopedia of cognitive sciences*. Cambridge, MA: The MIT Press.

Fabrikant, S. I. (2000). Spatialized browsing in large data archives. *Transactions in GIS, 4*, 65–78.

Fajen, B. R., & Warren, W. H. (2003). Behavioral dynamics of steering, obstacle avoidance, and route selection. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 343–362.

Feldman, A., & Acredolo, L. P. (1979). The effect of active versus passive exploration on memory for spatial location in children. *Child Development, 50*, 698–704.

Frederickson, R. E., & Bartlett, J. C. (1987). Cognitive impenetrability of memory for orientation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13*, 269–277.

Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: The MIT Press.

Gärling, T., Böök, A., & Lindberg, E. (1986). Spatial orientation and wayfinding in the designed environment: A conceptual analysis and some suggestions for postoccupancy evaluation. *Journal of Architectural Planning Resources, 3*, 55–64.

Gärling, T., & Gärling, E. (1988). Distance minimization in downtown pedestrian shopping. *Environment and Planning A, 20*, 547–554.

Gibson, J. J. (1950). *The perception of the visual world*. Boston: Houghton Mifflin.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.

Gladwin, T. (1970). *East is a big bird*. Cambridge, MA: Harvard University Press.

Golledge, R. G. (1987). Environmental cognition. In D. Stokols & I. Altman (Eds.), *Handbook of environmental psychology* (pp. 131–174). New York: Wiley.

Gopal, S., Klatzky, R., & Smith, T. R. (1989). NAVIGATOR: A psychologically based model of environmental learning through navigation. *Journal of Environmental Psychology, 9*, 309–331.

Gould, J. L., & Able, K. P. (1981). Human homing: An elusive phenomenon. *Science, 212*, 1061–1063.

Hardy, A. C. (1967). Landscape and human perception. In A. C. Murray (Ed.), *Methods of landscape analysis* (Vol. October, pp. 3–8). London: Landscape Research Group.

Hart, R. A., & Moore, G. T. (1973). The development of spatial cognition: A review. In R. M. Downs & D. Stea (Eds.), *Image and environment* (pp. 246–288). Chicago: Aldine.

Hazen, N. L., Lockman, J. J., & Pick, H. L., Jr. (1978). The development of children's representations of large-scale environments. *Child Development, 49*, 623–636.

Hickox, J. C., & Wickens, C. D. (1999). Effects of elevation angle disparity, complexity, and feature type on relating out-of-cockpit field of view to an electronic cartographic map. *Journal of Experimental Psychology: Applied, 5*, 284–301.

Hill, K. A. (Ed.). (1999a). *Lost person behaviour*. Ottawa, Ontario: The National Search and Rescue Secretariat.

Hill, K. A. (1999b). The psychology of lost. In K. A. Hill (Ed.), *Lost person behaviour* (pp. 1–16). Ottawa, Ontario: The National Search and Rescue Secretariat.

Howard, I., & Templeton, W. B. (1966). *Human spatial orientation*. New York: Wiley.

Hutchins, E. (1995). *Cognition in the wild*. Cambridge, MA: The MIT Press.

Johnson, M. (1987). *The body in the mind: The bodily basis of meaning, imagination, and reason*. Chicago: The University of Chicago Press.

Kerzel, D., Heiko, H., & Kim, N.-G. (1999). Image velocity, not tau, explains arrival-time judgments from global optical flow. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1540–1555.

Kirschvink, J. L., Jones, D. S., & McFadden, B. J. (Eds.) (1985). *Magnetic biomineralization and magnetoreception in organisms*. New York: Plenum Press.

Kitchin, R. (1998). *Cyberspace: The world in the wires*. Chichester: Wiley.

Kuipers, B. (1978). Modeling spatial knowledge. *Cognitive Science, 2*, 129–153.

Kuipers, B. (2000). The Spatial Semantic Hierarchy. *Artificial Intelligence, 119*, 191–233.

Lee, D. N., & Lishman, R. (1977). Visual control of locomotion. *Scandinavian Journal of Psychology, 18*, 224–230.

Levine, M. (1982). You-are-here maps: Psychological considerations. *Environment and Behavior, 14*, 221–237.

Levine, M., Marchon, I., & Hanley, G. L. (1984). The placement and misplacement of you-are-here maps. *Environment and Behavior, 16*, 139–157.

Levinson, S. C. (1996). Frames of reference and Molyneux's question: Crosslinguistic evidence. In P. Bloom, M. A. Peterson, L. Nadel, & M. F. Garrett (Eds.), *Language and space* (pp. 109–169). Cambridge, MA: The MIT Press.

Lewis, D. (1994). *We, the navigators: The ancient art of landfinding in the Pacific* (2nd ed.). Honolulu: University of Hawaii Press.

Llobera, M. (2003). Extending GIS-based visual analysis: The concept of visualscapes. *International Journal of Geographical Information Science, 17*, 25–48.

Lloyd, R. (2000). Understanding and learning maps. In R. Kitchin, & S. Freundschuh (Eds.), *Cognitive mapping: Past, present, and future* (pp. 84–107). London: Routledge and Kegan Paul.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., Cicinelli, J. G., Pellegrino, J. W., & Fry, P. A. (1993). Nonvisual navigation by blind and sighted: Assessment of path integration ability. *Journal of Experimental Psychology: General, 122*, 73–91.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., & Philbeck, J. W. (1999). Human navigation by path integration. In R. G. Golledge (Ed.), *Wayfinding behavior: Cognitive mapping and other spatial processes* (pp. 125–151). Baltimore, MD: Johns Hopkins Press.

Loomis, J. M., Klatzky, R. L., Philbeck, J. W., & Golledge, R. G. (1998). Assessing auditory distance perception using perceptually directed action. *Perception & Psychophysics, 60*, 966–980.

Lovelace, K. L., Hegarty, M., & Montello, D. R. (1999). Elements of good route directions in familiar and unfamiliar environments. In C. Freksa & D. M. Mark (Eds.), *Spatial information theory: Cognitive and computational foundations of geographic information science* (pp. 65–82). Berlin: Springer.

Lynch, K. (1960). *The image of the city*. Cambridge, MA: The MIT Press.

MacEachren, A. M. (1995). *How maps work: Representation, visualization, and design*. New York: Guilford Press.

Maguire, E. A., Burgess, N., Donnett, J. G., Frackowiak, R. S. J., Frith, C. D., & O'Keefe, J. (1998). Knowing where and getting there: A human navigation network. *Science, 280*, 921–924.

May, M., & Klatzky, R. L. (2000). Path integration while ignoring irrelevant movement. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 169–186.

McDermott, D., & Davis, E. (1984). Planning routes through uncertain territory. *Artificial Intelligence, 22*, 107–156.

McGranaghan, M., Mark, D. M., & Gould, M. D. (1987). Automated provision of navigation assistance to drivers. *The American Cartographer, 14*, 121–138.

McNaughton, B. L., Chen, L. L., & Markus, E. J. (1991). "Dead reckoning," landmark learning, and the sense of direction: A neurophysiological and computational hypothesis. *Journal of Cognitive Neuroscience, 3*, 190–202.

McNaughton, B. L., Knierim, J. J., & Wilson, M. A. (1995). Vector encoding and the vestibular foundations of spatial cognition: Neurophysiological and computational mechanisms. In M. S. Gazzaniga et al. (Eds.), *The cognitive neurosciences* (pp. 585–595). Cambridge, MA: The MIT Press.

Mittelstaedt, M. L., & Mittelstaedt, H. (1980). Homing by path integration in a mammal. *Naturwissenschaften, 67*, 566–567.

Mizumori, S. J. Y. (1994). Neural representations during spatial navigation. *Current Directions in Psychological Science, 3*, 125–129.

Montello, D. R. (1991). Spatial orientation and the angularity of urban routes: A field study. *Environment and Behavior, 23*; 47–69.

Montello, D. R. (1997). The perception and cognition of environmental distance: Direct sources of information. In S. C. Hirtle & A. U. Frank (Eds.), *Spatial information theory: A theoretical basis for GIS* (pp. 297–311). Berlin: Springer.

Montello, D. R. (1998). A new framework for understanding the acquisition of spatial knowledge in large-scale environments. In M. J. Egenhofer & R. G. Golledge (Eds.), *Spatial and temporal reasoning in geographic information systems* (pp. 143–154). New York: Oxford University Press.

O'Keefe, J. (1976). Place units in the hippocampus of the freely moving rat. *Experimental Neurology, 51*, 78–109.

O'Keefe, J., & Conway, D. H. (1979). Hippocampal place units in the freely moving rat: Why they fire where they fire. *Experimental Brain Research, 31*, 573–590.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. New York: Oxford University Press.

Paillard, J. (Ed.) (1991). *Brain and space*. Oxford: Oxford University Press.

Passini, R. (1992). *Wayfinding in architecture* (2nd ed.). New York: Van Nostrand Reinhold Company.

Pearsall, J., & Trumble, B. (Eds.) (1996). *The Oxford encyclopedic English dictionary* (3rd ed.). New York: Oxford University Press.

Piaget, J., Inhelder, B., & Szeminska, A. (1960). *The child's conception of geometry*. London: Routledge and Kegan Paul.

Pick, H. L., Heinrichs, M. R., Montello, D. R., Smith, K., Sullivan, C. N., & Thompson, W. B. (1995). Topographic map reading. In P. A. Hancock, J. M. Flach, J. Caird, & K. J. Vicente (Eds.), *Local applications of the ecological approach to human-machine systems, Vol. 2* (pp. 255–284). Hillsdale, NJ: Lawrence Erlbaum Associates.

Pick, H. L., & Palmer, C. F. (1986). Perception and representation in the guidance of spatially coordinated behavior. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 135–145). Dordrecht: Martinus Nijhoff Publishers.

Potegal, M. (1982). Vestibular and neostriatal contributions to spatial orientation. In M. Potegal (Ed.), *Spatial abilities: Development and physiological foundations* (pp. 361–387). New York: Academic Press.

Poucet, B. (1993). Spatial cognitive maps in animals: New hypotheses on their structure and neural mechanisms. *Psychological Review, 100*, 163–182.

Proctor, J. D. (1998). The social construction of nature: Relativist accusations, pragmatist and critical realist responses. *Annals of the Association of American Geographers, 88*, 352–376.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 1157–1165.

Rieser, J. J., Guth, D. A., & Hill, E. W. (1986). Sensitivity to perspective structure while walking without vision. *Perception, 15*, 173–188.

Ruddle, R. A., Payne, S. J., & Jones, D. M. (1997). Navigating buildings in 'desk-top' virtual environments: Experimental investigations using extended navigational experience. *Journal of Experimental Psychology: Applied, 3*, 143–159.

Ruggles, A. J., & Armstrong, M. P. (1997). Toward a conceptual framework for the cartographic visualization of network information. *Cartographica, 34*, 33–48.

Schacter, D. L., & Tulving, E. (Eds.) (1994). *Memory systems 1994*. Cambridge, MA: The MIT Press.

Shepard, R. N., & Hurwitz, S. (1984). Upward direction, mental rotation, and discrimination of left and right turns in maps. *Cognition, 18*, 161–193.

Schöne, H. (1984). *Spatial orientation: The spatial control of behavior in animals and man* (translated from German, *Orientierung im Raum*, by Camilla Strausfeld). Princeton, NJ: Princeton University Press.

Streeter, L. A., Vitello, D., & Wonsiewicz, S. A. (1985). How to tell people where to go: Comparing navigational aids. *International Journal of Man/Machine Studies, 22*, 549–562.

Tandy, C. R. V. (1967). The isovist method of landscape survey. In A. C. Murray (Ed.), *Methods of landscape analysis* (Vol. October, pp. 9–10). London: Landscape Research Group.

Tarr, M. J., & Bülthoff, H. H. (Eds.) (1998). *Object recognition in man, monkey, and machine*. Cambridge, MA: The MIT Press.

Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology, 14*, 560–589.

Tversky, B. (1992). Distortions in cognitive maps. *Geoforum, 23*, 131–138.

Warren, D. H., Rossano, M. J., & Wear, T. D. (1990). Perception of map-environment correspondence: The roles of features and alignment. *Ecological Psychology, 2*, 131–150.

Warren, W. H., Young, D. S., & Lee, D. N. (1986). Visual control of step length during running over irregular terrain. *Journal of Experimental Psychology: Human Perception and Performance, 12*, 259–266.

Waterman, T. (1989). *Animal navigation*. New York: Scientific American Library.

Wehner, R. (1996). Middle-scale navigation: The insect case. *Journal of Experimental Biology, 199*, 125–127.

Wehner, R. (1999). Large-scale navigation: The insect case. In C. Freksa & D. M. Mark (Eds.), *Spatial information theory: Cognitive and computational foundations of geographic information science* (pp. 1–20). Berlin: Springer.

Wehner, R., Lehrer, M., & Harvey, W. R. (Editors). (1996). Navigation: Migration and homing [Special issue]. *The Journal of Experimental Biology, 199*(1).

Weisman, J. (1981). Evaluating architectural legibility: Way-finding in the built environment. *Environment and Behavior, 13*, 189–204.

Yeap, W. K. (1988). Towards a computational theory of cognitive maps. *Artificial Intelligence, 34*, 297–360.

Yoshino, R. (1991). A note on cognitive maps: An optimal spatial knowledge representation. *Journal of Mathematical Psychology, 35*, 371–393.