

## CHAPTER 1

# Spatial Mental Representation: Implications for Navigation System Design

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Similarities exist in how people process and represent spatial information and in the factors that contribute to disorientation, whether one is moving through airspace, on the ground, or surgically within the body. As such, design principles for presenting spatial information should bear similarities across these domains but also be somewhat specific to each. In this chapter, we review research in spatial cognition and its application to navigation system design for within-vehicle, aviation, and endoscopic navigation systems. Taken together, the research suggests three general principles for navigation system design consideration. First, multimedia displays should present spatial information visually and action and description information verbally. Second, display organizations should meet users' dynamic navigational goals. Third, navigation systems should be adaptable to users' spatial information preferences. Designers of adaptive navigation display technologies can maximize the effectiveness of those technologies by appealing to the basic spatial cognition processes employed by all users while conforming to user's domain-specific requirements.

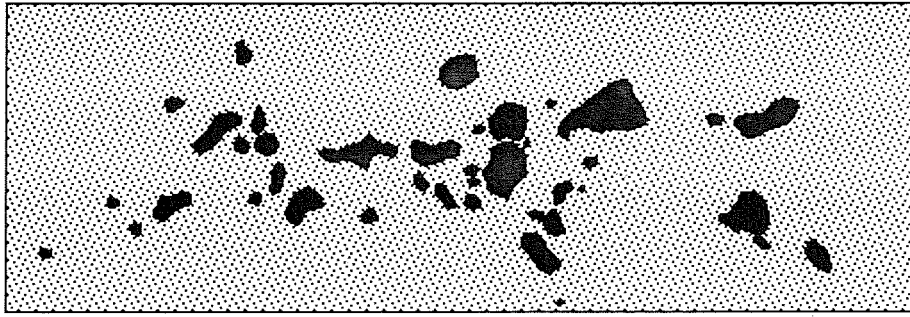
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*Waves, winds, clouds; stars, sun, moon; birds, fish and the water itself comprise about all there is to be seen, felt, heard or smelled. All of these have probably been used by every native navigator in the tropical Pacific. (Gladwin, 1970, p. 145, on describing Puluwat navigation)*

Whether sailing, walking, driving, or flying, people are engaged constantly in monitoring, controlling, and updating their position with respect to their immediate and remote environments. Often, these processes occur rapidly and with precision, as evidenced by the ease with which most people can navigate from home to work, from work to the store, and so on. Other times, people can have quite a bit of difficulty, such as when navigating complex, dynamic, or unfamiliar environments (Cornell & Hill, 2005; Heth & Cornell, 1998, 2006).

Pacific Islanders such as the Puluwat wayfind in the complex arrangement of the Caroline Islands (see Figure 1.1) with remarkable facility and without the support of compasses, chronometers, charts, or sextants (Gladwin, 1970; see also Lewis, 1970). In contrast, most people in the rest of the world wayfind via aided navigation using maps (route, topographic, etc.), detailed verbal spatial descriptions, global positioning systems (GPS), or even virtual reality.

In this chapter, we describe recent research in spatial cognition that has led to clear



**Figure 1.1.** Schematic map of a portion of the Caroline Islands, Micronesia, illustrating the complexity of the island layout.

guidelines that human factors/ergonomics (HF/E) researchers and engineers can use when designing and developing navigational aids.

## Wayfinding Versus Navigation

Although the behavioral, cognitive, and neural processes involved during wayfinding and navigation are typically treated as synonymous in the literature, important distinctions exist among these processes. Wayfinding is, aptly, the behavior of finding one's way from an origin to one or more destinations; in conventional terms, wayfinding relies on an existing understanding of an environment's spatial characteristics. In the case of the Puluwat, this involves extensive knowledge of celestial organization. In most other parts of the world, this understanding relies on existing spatial knowledge gathered from prior navigational experience, maps, or verbal descriptions. The cognitive mechanisms involved during wayfinding center on the retrieval and application of existing spatial representations.

The nature of these spatial mental representations may vary as a function of at least the following: *extent of experience* (Brunyé & Taylor, 2008a; Foo, Warren, Duchon, & Tarr, 2005; Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982), *nature of experience* (e.g., Montello, Hegarty, Richardson, & Waller, 2004; Noordzij, Zuidhoek, & Postma, 2006), *environmental scale and complexity* (e.g., Foo et al., 2005; Vallortigara, Feruglio, & Sovrano, 2005), and *individual differences* (e.g., Fields & Shelton, 2006; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). In general, with extensive experience, people can develop abstracted, comprehensive, and functionally useful mental models of an environment; these models can be accessed later when solving complex wayfinding tasks and do not rely on simple motor response sequences (e.g., turn left, go one block).

Some experienced taxi drivers demonstrate a phenomenal ability to wayfind (e.g., from the airport to your home) without navigational aids, presumably drawing on an extensive experience-based spatial mental model. Chase (1983) demonstrated that experienced taxi drivers generate novel routes and remember street names better than do novices. This notion is supported by research demonstrating superior wayfinding skills in London taxi drivers relative to pedestrians and bus drivers; corresponding posterior hippocampal neurogenesis is thought to reflect the development, storage, and use of a complex spatial representation (Maguire et al., 2000, 2003; Maguire, Woollett, & Spiers, 2006).

Navigation is a special case when wayfinding is done using either simple stimulus-response motor sequences or one or more supportive mechanisms. That is, although all wayfinding necessarily relies on some information, true wayfinding derives information naturally from the dynamic between comprehensive spatial knowledge and positioning within an environment. Navigation, in contrast, does not necessitate the recruitment of spatial representations *per se* but, rather, an understanding of how a memorized sequence of motor procedures or a particular navigational aid (map) should be used (Hartley, Maguire, Spiers, & Burgess, 2003; O'Keefe & Nadel, 1978). Compared with wayfinding, navigation is more passive, in that a person follows (rather than derives) a prescribed series of turns and distances. Navigation is less cognitively complex, in that it does not necessitate the recruitment or application of complex spatial representations.

Take the following example from aviation. A student pilot is navigating when flying a box pattern around the airfield under visual flight rules (VFR). She performs a takeoff and climbs to 1,500 feet above ground level and levels off, turns 90 deg to the right and flies that heading for 60 s or until she is over the eastern edge of the kidney-shaped pond, turns 90 deg to the right and flies that heading until the approach end of the runway disappears over her right shoulder, and turns 90 deg to the right and observes the approach end of the runway so she can roll out after her next 90-deg turn aligned with the runway. After 30 more flight hours, this same student pilot might be capable of wayfinding; for example, flying VFR cross country from her present position to an airfield 30 nautical miles northwest, entering the traffic pattern, and landing on Runway 15.

Work in cognitive neuroscience supports the distinction between wayfinding and navigation by demonstrating that differential brain activation occurs during route following (e.g., caudate nucleus) versus wayfinding (e.g., right posterior hippocampus; see Hartley et al., 2003; Maguire, Frackowiak, & Frith, 1997; Packard & McGaugh, 1996; Spiers & Maguire, 2006). The caudate nucleus is involved in learning and applying voluntary movements (Packard & Knowlton, 2002) and motor control (Wilson, 1912); in contrast, the right posterior hippocampus is involved in storing and using complex spatial information (Maguire et al., 2000; Moser, Moser, & Anderson, 1993; O'Keefe & Nadel, 1978). It should be clear that there are several behavioral, cognitive, and neural distinctions between wayfinding and navigation. In this chapter, we deal mostly with processes applicable to human systems design—navigation.

## **Spatial Cognition in Navigation: Human Factors Issues**

Our goal in this chapter is to present recent findings in spatial cognition that have important implications for the human factors of navigation systems. Knowledge of spatial cognition is exceedingly important when considering the inevitable complexity of human behavior and cognition, as well as its important interactions with environmental variables. Paradoxically, although navigation appears to be behaviorally and cognitively simple compared with wayfinding, the design of useful technology to aid navigation is exceedingly complex (Brunyé, Taylor, & Worboys, 2007; Wickens, Vincow, & Yeh, 2005). Difficulties in design stem from at least three global issues: dynamic user tasks and goals, varying user experience along with existing and resulting memories, and infinitely complex environments within which users operate.

People move through environments for different reasons. A London taxi driver in training may do so with the goal of acquiring a comprehensive model, or mental map, of the city (i.e., Maguire et al., 2006); this same taxi driver may later move through the environment only with the goal of getting from an origin to a destination as quickly as possible. A London tourist may move through the same environment to learn about particular landmarks (e.g., Big Ben, Tower of London) but may also rent a car, encounter a construction detour, and need to access information about the overall environmental configuration to find an alternate route. In yet another example, World War II German bomber pilots sought particular London landmarks as strategic bombing targets but subsequently needed to find their way back to their operating base while avoiding hostile areas.

Taxi drivers, tourists, and even pilots may use similar maps, but each is likely to develop largely different mental representations of the environment because of their varying goals. In fact, people instructed to navigate an environment with one of two goals—to learn particular routes (route goal) or to learn its overall layout (survey goal)—tend to remember different things (Taylor, Naylor, & Chechile, 1999). Those with a route goal better represent paths between particular locations and perform well on memory tests of path distances; in contrast, those with a survey goal tend to represent the environment's configuration and perform well on tests of Euclidian (straight-line) distances. These effects appear to result from goal-directed visual perception during learning and, in turn, mental representations that are better or worse suited to perspective switching (Brunyé & Taylor, 2008a).

Clearly, perspective goals during navigation can affect the content and structure of eventuating mental representations. The inevitable goal variation across and within individual users is a major challenge facing those who design effective navigation devices: How can a device present information in a manner congruent with or adapt to widely variable user goals? We intend to provide some insight into this problem by reviewing recent work in goal orientation and spatial mental model development.

A navigator's experience with a particular environment will also influence an eventuating mental representation. London taxi drivers with 1 week versus those with 1 year of training have very different representations of the city (i.e., Chase, 1983; Kalakoski & Saariluoma, 2001) and can do certain things without, and other things only with, a navigational aid. Analogously, someone visiting London for a week versus another who visits for a year will also have different representations of the city. The effect of experience has broad-based implications for navigation system design, including the elimination of extraneous information, reduction in cognitive load, and increase in specificity. We return to these issues when we consider the application of spatial cognition research to particular human factors/ergonomics problems.

A final influence, complementing user goals and experience, is related more to the environment than to the navigator: environmental complexity. Environments vary in their inherent complexity in a variety of ways, such as landmark size, shape, and density; path network structure; topography; and stability over time. The more complex the environment on one or more of these dimensions, the more likely a user will need navigation assistance. The level of detail (granularity) a user needs is contingent on the complexity of the navigated environment. In general, the higher the complexity, the more detail necessary to navigate (most Bostonian drivers will attest to this!). Unfortunately, greater detail

leads also to higher cognitive load (Brunyé et al., 2007; Schneider & Taylor, 1999), which emphasizes the importance of empirically sound navigation system design principles.

These three influences—user goals, user experience, and environment complexity—are measurable in isolation but are also dynamic and interactive, and they are never applied in a vacuum. User goals change, user knowledge increases inevitably with experience, and environments are infinitely detailed and ever changing. Spatial cognition research findings can guide thinking on the human factors/ergonomics of navigational aids.

## COGNITIVE MECHANISMS IN NAVIGATION AND WAYFINDING

### Mental Representations of Spatial Information

Early research on navigation, both human and animal, focused on the importance of action-based sequences in dictating success in navigating familiar environments. Sequences such as “When you see the library, turn left” also include a perceptual component, and researchers have found that individuals rely solely on these perceptible cues to guide decision making and movement through an environment (e.g., Hull, 1932; Hull & Spence, 1938; Thorndike, 1903, 1919). Upon encountering a familiar landmark (i.e., the library), the navigator retrieves and applies a simple action sequence (e.g., turn left) that best fits a particular goal. This basic stimulus-response theory aligns well with behaviorist accounts of human learning and memory.

In an applied sense, this theory has been used successfully to develop *wayfinding choremes*, or basic stimulus (e.g., intersection) and response (e.g., sharp left) schemas, that guide navigators to their destinations (Klippel, 2003; Klippel, Tappe, Kulik, & Lee, 2005). Theoretically, however, these stimulus-response accounts of navigation cannot explain common experiences, seen in both humans and animals, of computing and following *novel* paths to effectively reduce time and distance to a goal (i.e., shortcutting; Tolman, 1948; Tolman, Ritchie, & Kalish, 1946).

To account for short-cutting behaviors, researchers proposed that people (and animals) actively construct *cognitive maps* or “maps in the head” that provide two-dimensional representations analogous to human-made maps (e.g., Appleyard, 1970; Ladd, 1970; O’Keefe & Nadel, 1978; Sholl, 1987; Tversky, 1993). These maps provide a “bird’s-eye” memory of an environment that navigators can recruit when faced with complex spatial problems, such as short-cuts or detours. Compared with action sequences, cognitive maps provide greater perspective and orientation flexibility—that is, they are not inextricably tied to actual experiences with the environment. This characteristic accounts for one’s ability to travel two separate routes and then locate a novel path between them without using a map or other navigational aid (e.g., Fukusima, Loomis, & DaSilva, 1997; Gould, 1986; Klatzky, Loomis, Beall, Chance, & Golledge, 1998).

Cognitive maps are not an inevitable result of experience, however; only with extended experience are individuals able to develop these maplike representations (Brunyé & Taylor, 2008a, 2008b; Gallistel, 1990; Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982). Navigation within an unfamiliar or simple environment often incorporates action-based

sequences, whereas movement within complex environments appears to necessitate a cognitive map. This view aligns well with work in cognitive neuroscience (i.e., lesioning studies, structural and functional brain imaging) demonstrating that distinct brain areas are associated with action-based and cognitive map-based processes (i.e., Maguire et al., 1998; Maguire, Frackowiak, & Frith, 1996, 1997).

The structure of the cognitive map, however, remains a point of debate. Some researchers support *positional coding models* and argue that individuals code landmark positions within the environment (e.g., Devlin, 1976; Hermer & Spelke, 1994; Wang & Spelke, 2000). Others support an *associative model*, wherein direct relationships between landmarks are coded (e.g., Kaplan, 1976; Mou & McNamara, 2002; Schölkopf & Mallot, 1995). Still other work suggests that cognitive maps incorporate both layout (positional) and relatively fine-grained landmark interrelationship (associative) information (e.g., Newman et al., 2007).

Some researchers have demonstrated that neither action-based sequences nor relatively advanced cognitive maps can fully account for complexities of spatial memory and behavior. Mental representations of space are subject to the mental processes that form and maintain them. Specifically, researchers have demonstrated that spatial mental representations can be distorted by the following:

- a. *categorical and hierarchical information*, such as conceptual boundaries or even group social status hierarchies (Hirtle & Jonides, 1985; Hirtle & Mascolo, 1986; Lakoff, 1987; Maddox, Rapp, Brion, & Taylor, 2008; Maki, Maki, & Marsh, 1977; McNamara, 1991; McNamara, Hardy, & Hirtle, 1989; Stevens & Coupe, 1978; Tversky, 1991);
- b. *reference points and biases*, such as judging the distance from a salient landmark (e.g., Eiffel Tower) to a relatively ordinary one (e.g., a café) as farther than the opposite distance (Sadalla, Burroughs, & Staplin, 1980);
- c. *regularization of boundaries and relationships*, such as judging borders and rivers as straighter, intersections as closer to right angles, and familiar routes as lengthier when they contain barriers, detours, clutter, or multiple turns (Newcombe & Liben, 1982; Sadalla & Montello, 1989; Thorndyke, 1981);
- d. *actions* undertaken while moving within the environment, even if irrelevant to motion (e.g., May & Klatzky, 2000); and
- e. *individual goals, preferences, and biases* such as a preferential, goal-driven, or motivational biases toward particular perspectives (DeBeni, Pazzaglia, & Gardini, 2006; Pazzaglia & DeBeni, 2001; Taylor et al., 1999).

Basic cognitive map theory, with its analogue format, does not predict that people will impose categories, hierarchies, reference points, and regularization strategies on spatial memory.

To account for these findings, researchers recently have proposed that spatial memory is more layered, collage-like, and three-dimensional, much like a designer or architect's 3-D computer model (deVega, Intons-Peterson, Johnson-Laird, Denis, & Marschark, 1996; Taylor, 2005; Taylor & Tversky, 1992; Tversky, 1991, 1993). These models support added layers of spatial and nonspatial information relevant to the complete representation of an environment, such as images, sounds, descriptions, smells, and the navigator's arousal state (Brunyé, Mahoney, Augustyn, & Taylor, 2008; McNamara, Halpin, & Hardy, 1992a). They also support spatial information retrieval from multiple perspectives and orientations with high accuracy and fluidity, account for the presence of biases and heuristics

in human spatial memory, and support the reorganization of these memories based on individual goals, preferences, and biases.

Critically, these models develop only out of extensive first-hand experience and are vulnerable to influences of nonspatial environmental characteristics (McNamara, Halpin, & Hardy, 1992a, 1992b; Tversky, 1993). For example, as our student pilot logs more flying hours, she may perceive the distance between the airfield and her practice area to have increased; in reality, her perception may be affected by decreased task saturation and increased situation awareness as her flying skills improve. Similar changes in perception may result from flying a faster plane or encountering poor weather conditions.

Another spatial memory form to consider is the *spatial mental model*. This term has been applied generally to memory representations resulting from reading descriptions about environments, such as a description of a path through a village or one detailing a city's overall layout (i.e., Brunyé & Taylor, 2008a, 2008b; Noordzij & Postma, 2005; Taylor, 2005; Taylor & Tversky, 1992; Tversky, 1991). Spatial mental models go beyond the text level of a description to mentally represent spatial information in an abstracted and flexible manner. For instance, when individuals read descriptions of a route through an environment or about the layout of an environment, they form memories that can be applied flexibly across perspectives (e.g., drawing a map after learning a route, verifying first-person perspective statements after learning a layout) and orientations (Brunyé & Taylor, 2008a, 2008b; Noordzij & Postma, 2005; Taylor, 2005; Taylor & Tversky, 1992). The abstracted structure of spatial mental models is analogous to the memory representations that account for findings showing that readers go beyond the text to represent described situations (Johnson-Laird, 1983; Perrig & Kintsch, 1985; vanDijk & Kintsch, 1983). Although generally used in the context of spatial descriptions, spatial mental models also may develop from other sources, particularly when multiple sources combine to inform one about an environment.

Thus we can distinguish among at least four general forms of mental representation to account for human cognition and navigation behaviors: *action-based procedural representations*, *cognitive maps*, *cognitive collages*, and *spatial mental models*. In the following section, we use the term *cognitive map* to describe the mental representations resulting from both first-hand experience and the use of navigational aids. We do not intend to say that human spatial representations maintain analogue forms in memory; rather, we use *cognitive map* as a ubiquitous term and a useful metaphor for explaining and understanding human navigation and wayfinding.

## Constructing Cognitive Maps

The manner in which humans develop spatial memories is as complex and varied as the experiences that engender them. Broadly speaking, spatial information sources can be abstracted forms that are studied and physical spaces experienced through navigation. Abstracted forms include maps, atlases, globes, geographical information and global positioning systems, personal digital assistants, and even virtual reality (Golledge, 1992; Hirtle & Sorrows, 2007). These forms can be either close to or far removed from actual experience. The successful development of navigational aids relies on delineating features that reliably lead to the development of cognitive maps that navigators can use even when

unaided. In this section, we introduce four human and technological characteristics that have proven important toward successful human-systems design.

**Symbolic extrapolation.** *Symbolic extrapolation* is the process by which relevant elements of an environment are extracted into symbolic form. An individual attends to, interprets, infers, and stores these symbols in spatial memory. All maps (electronic and conventional) have varying levels of symbolic detail, are more or less accurate, and are more or less difficult to interpret. Consider studying an information map at a mall. In so doing, your aim is to identify the location of a goal destination (e.g., restrooms), then identify your present location and its relation to the destination, and, finally, determine the best route between the two. The first step involves locating a symbol for the restrooms (e.g., a schematic of a man and woman separated by a vertical line) and then temporarily holding the restroom location in working memory. The next step is to determine your location, which is often accomplished by locating a "you are here" indicator. This step often also involves determining the map's orientation relative to the actual environment (Levine, Marchon, & Hanley, 1984). Your own location also must be maintained in memory to compute a route to the destination. Next, you compare the present location with that of the restroom and plan a route. Finally, you must scan the environment, assess your location relative to the chosen route, begin travel, and constantly reassess your dynamic location relative to the route and goal (i.e., Jul & Furnas, 1997; Levine et al., 1984).

Of particular note is the ability for humans to quickly recognize and interpret the symbol relevance, particularly in dense displays. It is well established that low map density and high interpretability lead to faster search times and broader understanding (Florence & Geiselman, 1986; Schober & Conrad, 1997). In contrast, increasing map density increases both search times and working memory load and leads to generally poorer eventuating memory (Brunyé, Taylor, & Worboys, 2007; Florence & Geiselman, 1986; Moreno & Mayer, 2000). That is, developing cognitive maps can be affected by the relative ease with which information can be extracted from spatial displays. One alternative, of course, is to use verbal labels and descriptions rather than relying on the successful extraction of information from often ambiguous symbols; these forms, however, require a certain degree of literacy and linguistic invariance.

In considering the ubiquity of electronic and traditional navigational aids, it becomes clear that emphasis should be placed on developing and using symbolic standards (MacEachren, 1995; Robinson, Sale, Morrison, & Muehreke, 1984) and minimizing irrelevant information in displays. In effect, the ability to develop and apply cognitive maps is contingent on extrapolating relevant (and often critical) information from complex displays. The best symbols are those that do not require complex inferences and are relevant to the navigator's intention. Determining relevant information by task goals should be a primary objective of future work (i.e., via task analyses), along with identifying broadly interpretable symbol systems for maps (Klippel, Freksa, & Winter, 2006; MacEachren, 1995).

**Landmarks.** The landmarks displayed on an information source may be critical in guiding navigation (Heidorn & Hirtle, 1993; Nothegger, Winter, & Raubal, 2004; Siegel & White, 1975; Tversky, 1993). Recent work shows that humans, unlike several other animals, may rely strongly on visual landmarks, especially during early environment learning



(Foo et al., 2005). Reliable and salient visual landmarks guide locomotion and provide preliminary structure for a developing cognitive map (Klippel & Winter, 2005). In contrast, unreliable or visually unavailable landmarks force reliance on path integration and dead reckoning.

Other research has demonstrated that people have less difficulty and better route and recognition memory when using landmarks versus street names during navigation (Tom & Denis, 2003, 2004). In general, landmarks play primary roles in guiding navigators toward destinations and in facilitating spatial memory (Daniel & Denis, 2004; Daniel, Tom, Manghi, & Denis, 2003; Denis, 1991, 1997; Denis, Pazzaglia, Cornoldi, & Bertolo, 1999; Klippel & Winter, 2005; Raubal & Winter, 2002; Schneider & Taylor, 1999; Weissensteiner & Winter, 2004). This strongly suggests structuring information interfaces around landmarks that are reliable, salient, and distinctive and that correspond to decision points along a path (Klippel & Winter, 2005; Raubal & Winter, 2002; Sadalla et al., 1980; Weissensteiner & Winter, 2004).

**Perspective on environment.** The perspective on an environment may play a role in the nature of resulting spatial memory. Spatial displays can be represented from a bird's-eye perspective to a ground-level, first-person perspective and anywhere in between (e.g., a three-quarter view). Perspective is related to the *frame of reference*, which mentally structures spatial relations (e.g., satellite or worldview that displays spatial information with regard to canonical coordinates vs. an egocentric view that displays space from an observer's view). The varied frames of reference on an environment affect processing speed and cognitive map construction.

Consider the case of operating a motor vehicle, which is done at the ground level using the position of the vehicle and the self as frames of reference for interpreting movement within the environment (i.e., McCormick, Wickens, Banks, & Yeh, 1998; Wickens et al., 2005; Yeh, Merlo, Wickens, & Brandenburg, 2003; Yeh, Wickens, & Seagull, 1999). In-vehicle navigation systems may present information either consistent with the driver's view, using a driver or vehicle reference frame, or inconsistent with the driver's view, using a world (bird's-eye) reference frame (i.e., Wickens, Ververs, & Fadden, 2004). The bird's-eye reference frame itself can vary, maintaining an orientation consistent either with the forward-motion direction (heads-up display or track-up) or with canonical north (north-up display). Some systems may switch between these views on command or switch from the world to vehicle reference frame at decision points, such as intersections. Still others maintain a three-quarter view, consistent with the direction of travel, providing a viewpoint between bird's-eye and embedded within the environment.

What role do reference frames play in constructing cognitive maps, how do individual differences play a role, and how can these effects inform systems design? Christopher Wickens's group examined the effectiveness of egocentric and exocentric displays toward safe and efficient navigation with pilots. Much of the work finds that first-person egocentric views from the nose of an aircraft are superior to other variations of exocentric and coplanar views (Haskell & Wickens, 1993; Olmos, Wickens, & Chudy, 2000; Wickens & Prevet, 1995). The notion is that coupling the pilot view with the aircraft view requires minimal transformation and increases perceived presence within an environment. Not surprisingly, some researchers have demonstrated that spatial transformations, such as

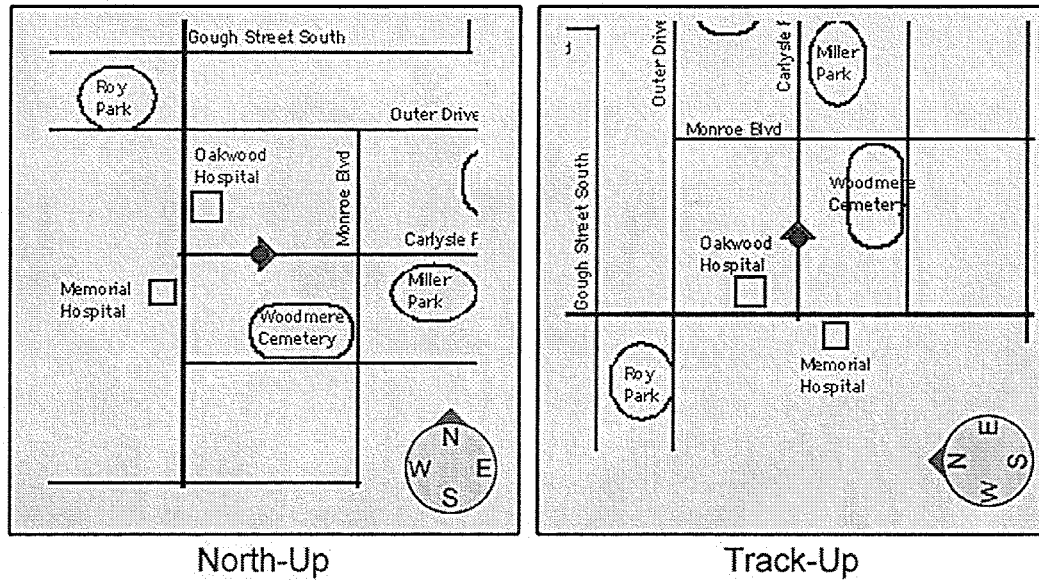
switching from one reference frame to another, can be disorienting (Olmos et al., 2000). Other work, however, has shown that allowing users to control these switches (Ruddle, Payne, & Jones, 1999) or providing common elements across reference frames (e.g., highlighting a particular area of space; Aretz, 1991) might lessen disorientation. Further work has demonstrated that egocentric views are especially useful when screen size can represent a broad visual field; with small screens, allocentric displays may prove more beneficial (Tan, Gergle, Scupelli, & Pausch, 2003, 2004).

Overall, the frame of reference adopted in spatial displays can affect people's ability to understand spatial information and translate it into successful navigation. The cognitive maps resulting from extended experience with both egocentric and allocentric displays tend to be different. A north-up map often leads to inflexible spatial memories that are tightly bound to the initially learned orientation (Evans & Pezdek, 1980; Levine et al., 1984; Sholl, 1987). In contrast, extended egocentric experiences, such as in virtual environments or while reading route spatial descriptions, tend to produce flexible memory representations that can be applied across a variety of orientations (Brunyé & Taylor, 2008a; Foo et al., 2005; Noordzij & Postma, 2005). Of course, individual differences make blanket statements regarding perspective specificity and flexibility somewhat misleading. Individuals clearly vary with regard to preferred perspectives, their dependence on landmarks as navigational aids versus recruiting "mental maps," sense of direction, and visuospatial abilities (e.g., Hegarty et al., 2006; Hegarty & Waller, 2004, 2005; Pazzaglia & DeBeni, 2001).

**Orientations.** Related to what was mentioned earlier, orientations experienced within environments can play a role in the resulting cognitive maps. *Orientation* refers to the viewpoints one can take within a given perspective; within a route (first-person, within-environment) perspective, navigators can experience few or many orientations. For instance, traversing the state of Massachusetts on rural routes inevitably will enable one to experience multiple orientations relative to traversing the state on the east-west-running turnpike. In general, experiencing multiple orientations is beneficial in cognitive map development; limited orientations, in contrast, limit the scope and flexibility of such mental representations. That is, multiple orientations allow for flexibility in representational form, enabling one to integrate this information into a unitary and comprehensive map (Gallistel, 1990).

Orientation is a critical aspect of any navigation system. Matching the displayed orientation—either egocentric or allocentric—is optimal for requiring the fewest transformations toward understanding. One example of this is driving with a dynamic position indicator on a map that either keeps a north-is-up orientation ("north-up") or varies map orientation in correspondence with driving direction ("track-up"). In the former, the driver has a consistent map orientation but is required to transform the vehicle orientation; for instance, when the destination is south on a map (e.g., Woodmere Cemetery) and the vehicle is heading east, the driver must transform this into a "turn right" (see Figure 1.2).

The consistent orientation of the map and the transformation/rotation processes necessary for navigation may facilitate memory in two primary ways. First, the consistent map image may ease the transition from a visual percept to a mental representation; and second, the active processing necessary in rotating the map to derive a turn direction may



**Figure 1.2.** Examples of north-up (left panel) and track-up (right panel) navigation system display orientations.

help establish more flexible representations. In the track-up case, the map rotates so that the vehicle-forward direction is always displayed upward. As such, a direction to “turn right” is obvious from the display. Such a design is likely helpful in navigation but less so in cognitive map development: The map directly conveys turn information but does not remain in a single orientation or demand active mental rotation.

Some work has supported these distinctions by demonstrating that navigation performance is generally facilitated by track-up maps, but cognitive map development is enhanced using north-up maps (Aretz, 1991; Aretz & Wickens, 1992; Shepard & Hurwitz, 1984; Tlauka, Stanton, & McKenna, 2000). The successful application of technology likely arises out of close examination of user goals. Displaying multiple orientations in a track-up fashion may prove best in navigating to a particular destination but has less utility in learning the layout of the environment for subsequent unaided navigation. Spatial scale would also play a role. North-up maps make global spatial information salient, whereas track-up maps emphasize local information, and this would interact with scale (Tlauka et al., 2000). Furthermore, track-up maps may be especially useful in driving situations with a high cognitive load, in which display viewing and mental rotation tasks will detract from vehicle operation.

## Using Cognitive Maps in Navigation and Wayfinding

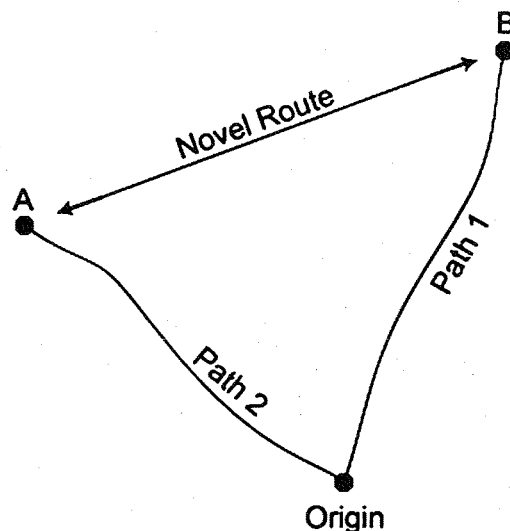
Users familiar with an area will most often navigate and wayfind without navigational aids and instead rely on the cognitive map that they have acquired through experience. In these cases, locomotion must rely on a variety of representational forms and cognitive processes. These representational forms likely vary, including visual landmark representations (i.e., mental images) and abstracted multidimensional representations that preserve metric and categorical information about regions, routes, topography, and landmarks.

Theories vary with regard to how integrated such representational forms might be in memory, when they may develop, which tasks they may serve, and their degree of automaticity toward goal-directed behavior.

In the strongest sense, cognitive maps are conceptualized as analogue allocentric map-like representations. Not surprisingly, then, these representations are useful for solving problems such as Euclidian distance estimation, route selection, novel path determination, and sketch map drawing. *Euclidian distance estimation* involves calculating crow's-flight distances between two locations; such a task is well supported by representations that preserve metric information, allow an allocentric perspective, and include rich detail regarding the relative location of landmarks (Taylor et al., 1999). *Route selection* involves deciding which of a series of routes is most congruent with the straight-line distance and direction between landmarks; some routes will correspond well (e.g., interstate highways between major cities) and some less well (e.g., state routes between a major city and a small town in the mountains). Successful route selection involves comparing alternative routes relative to a straight-line estimation while considering other extraneous variables (e.g., traffic, detours, density, tolls); in this sense, route selection goes beyond knowledge of route sequences to recruiting a cognitive map.

*Computing novel paths* through an environment is an additional affordance of cognitive maps; one simple example of this is *triangle completion* (Figure 1.3), which involves triangulating three landmarks within an environment without experiencing one of the three vectors. For instance, when individuals travel along two paths (Paths 1 and 2) emanating from a single origin to two separate destinations (A and B), they can often identify the novel route connecting the two destinations (Kearns, Warren, Duchon, & Tarr, 2002). This knowledge is often coarse, however, and likely involves mechanisms beyond the recruitment of a cognitive map (Foo et al., 2005).

Finally, an additional capability afforded by cognitive map representations is *sketch map drawing*. People draw maps to depict a route or the overall layout, but the cognitive map



**Figure 1.3.** The triangle completion task, depicting two traveled paths (1 and 2) and the novel route between the two destinations (A and B) that individuals are typically able to infer.

in particular is amenable to drawing maps in a sequence-invariant manner—that is, without regard to the manner in which the environment is conventionally experienced at the ground level.

Although cognitive maps are good at serving these kinds of tasks, they are also vulnerable to representational errors brought about through nonspatial influences (Tversky, 1991, 1993, 2000a, 2000b, 2005). Individuals tend to structure cognitive maps such that landmarks are aligned with one another on horizontal or vertical axes. For instance, one might align Boston and Albany on a shared horizontal axis or New York City and Washington, D.C., on a shared vertical axis. Cognitive maps tend to represent borders, routes, intersections, and landmarks as rotated into positions corresponding to one another and/or canonical coordinates. For example, one might sketch intersections at 90-deg angles or landmarks as facing due north, south, east, or west. Near distances are overestimated relative to far ones (Holyoak & Mah, 1982); functionally, politically, and linguistically similar landmarks are grouped together spatially (Hirtle & Jonides, 1985; Maddox et al., 2008; Portugali, 1993).

Clearly, the cognitive maps that result from actual experiences in an environment are far from a representational form with 1:1 perceptual-cognitive correspondence. That is, cognitive maps are biased by heuristics and extremely malleable in nature. Each of these heuristics can affect a person's ability to navigate to a destination with accuracy and efficiency.

In summary, navigators and wayfinders rely on their own mental representation or cognitive map, which is often coupled with navigational aids. Their reliance on such aids is a function of their experience with a particular environment. Furthermore, individuals wend their way through environments for many reasons—such as to find a particular location, learn the layout of a new hometown, or train for a taxi-driving career—and their cognitive maps reflect these goals.

Cognitive maps also incorporate nonspatial information, resulting in regularization and distortion of the cognitive map. In the next section, we consider the general implications of these influences on cognitive maps for the design of navigation systems.

## IMPLICATIONS FOR NAVIGATION SYSTEMS

### Spatial Information Sources

When navigating, people rely on different geographic information sources, including actual environment experience, maps, descriptions, or combinations of these. Actual experience includes following specific routes or just wandering through the environment; in both cases, the person experiences a within-environment perspective and locates landmarks with respect to his or her own (egocentric) location.

Maps and descriptions serve as secondary information sources. Maps provide a graphic analogue representation, generally with accompanying labels. People may study a map before and/or during navigation. Descriptions abstract spatial information to the level of language. Although information is abstracted, people build cognitive maps and update spatial memory from spatial language just as they do from maps (Loomis, Lippa, Klatzky,

& Golledge, 2002; Taylor & Tversky, 1992). The spatial information source can influence the experience with and, consequently, the memory for an environment (e.g., Shelton & McNamara, 2004; Thorndyke & Hayes-Roth, 1982), particularly early in learning. Evidence also suggests that after one has extensive experience, regardless of the source of that experience, the resultant mental representations become more similar (e.g., Brunyé & Taylor, 2008a; Taylor & Tversky, 1992; Thorndyke & Hayes-Roth, 1982). Navigation systems can incorporate one or more secondary sources. How might format differences in navigation systems influence their effectiveness in navigation and the information users will take away from them?

Depictions and descriptions of spatial information can be used individually or in combination. Navigational aids tend to combine direct experience with at least one, and often both, secondary information sources. Modern in-vehicle Global Positioning System-based navigation systems present maps visually and directions aurally. Cognitive theory would predict increased navigational effectiveness from aids combining graphic (map) and verbal (description) information (Baddeley, 2002; Paivio, 1986). This prediction is based on current conceptions of working memory and the benefits of dual coding on memory. Multimedia presentations, by definition, combine more than one format (e.g., words and pictures), whether it be within a single sensory modality (e.g., visual steps of a route map along with written descriptive information for reaching a destination) or across modalities (e.g., maps with voice-over navigational instructions). Multimedia displays have become popular, and research supports their effectiveness, relative to single-format sources, for a variety of information content (Allen, 1971; Brunyé, Taylor, Rapp, & Spiro, 2006; Kozma, 1991; Levie & Lentz, 1982; Mayer, 2001; Peeck, 1994). How might navigation systems best combine verbal and visual/spatial information? The cognitive mechanisms involved with multimedia processing provide useful guidelines.

The proposed cognitive mechanisms underlying the multimedia advantage include classic memory research, as outlined in Mayer's (1997) generative theory of multimedia learning, and include dual-coding theory (Paivio, 1986), current conceptions of working memory (Baddeley, 2002), and generative processing (Slamecka & Graf, 1978). *Dual-coding theory* posits simultaneous and independent processing of verbal and image information (Paivio, 1986), such that both information types are encoded, providing multiple routes to retrieval. Current conceptions of *working memory* support separate phonological and visuospatial "slave" systems with oversight and information routing and integration via the central executive (Baddeley, 1992). With this conceptualization, working memory resources can be better maximized when information combines verbal and image formats (Baddeley, 2002). The *generation effect* proposes that actively selecting and integrating information from multifformat displays may in itself facilitate memory (Slamecka & Graf, 1978).

In summary, the ability to simultaneously process text and images, in conjunction with the active integration and formation of new memories, helps create powerful memory associations that can be flexibly applied toward solving novel problems (e.g., Brunyé, Taylor, & Rapp, in press).

Although multimedia navigational aids theoretically would provide the greatest utility, the role of the individual spatial information source must be considered when determining how best to use them in combination. Maps provide analogue spatial information,

both local and global, although most maps are not purely spatial, because they often contain verbal labels. For navigation and wayfinding, local information in the form of individual landmarks and landmark-to-landmark spatial relations is critical in determining current location and orientation. Global information, in the form of landmark configuration and layout, comes into play more in planning routes, determining short-cuts, and finding alternative routes when confronted with a detour.

Both layout and landmark information appear to be learned relatively quickly and used for navigation (Newman et al., 2007). The separability of local and global spatial information is evident in the various neurological disorders generally cataloged under the heading of *topographic disorientation* (Aguirre & D'Esposito, 1999). Topographic disorientation, however, encompasses several disorders related to navigation and wayfinding, some of which show deficits of local information processing (e.g., landmark agnosia) and others of global processing (e.g., heading disorientation).

The relative availability of local and global information depends on the map's granularity (Stell & Worboys, 1999); increased graphic generalization favors global information. Different levels of granularity have implications for the preciseness of spatial information and, consequently, for wayfinding ability (Kuhn & Timpf, 2003). As such, a map's granularity affects its utility, depending on the navigational goal and the environmental complexity. For the design of navigation systems, the granularity at which the system displays maps should be coupled to the environmental complexity and the current navigation goal. One method is automatic decluttering of irrelevant information (e.g., Parasuraman & Byrne, 2003), and another is manual decluttering via the user interface (e.g., Smith & Murchie, 1991).

When serving as a single-format source, verbally presented (visual or auditory) spatial information involves either action sequence commands for route following or descriptions of entire environments. Verbal information, such as maps, can vary in their level of detail. Granularity in descriptions is operationalized through under- or overdetermining the spatial information included and has implications for spatial memory and wayfinding (e.g., Brunyé, Taylor, & Worboys, 2007).

Schneider and Taylor (1999) found navigation decrements with indeterminate and overdeterminate descriptions. Both cases tax working memory, but for different reasons. Indeterminacies preclude information from being integrated into a unified mental model and necessitate the maintenance of verbatim information within working memory (Mani & Johnson-Laird, 1982). In contrast, overdeterminacies tax working memory with too much information, necessitating decisions about information relevance or maintenance of all information (Schneider & Taylor, 1999). Thus, the verbal spatial information should be limited to, but completely inclusive of, spatial information necessary for a particular navigational goal.

Lesser-used spatial information sources incorporate 3-D sound (Loomis, Klatzky, Philbeck, & Golledge, 1998; Loomis et al., 2002) or vibrotactile information (van Erp, 2001). These information sources generally have been examined as substitutions when visual input is degraded (e.g., blindness, limited field of view) or overtaxed (e.g., highly complex environment). With 3-D sound, beeps or voices emanate from a target location that can then be localized. In a navigation system for the blind, sound beacons containing landmark information could be placed throughout an environment. Individuals use sound for

both direction and distance information with good success and little need for training (e.g., Loomis et al., 1998, 2002), suggesting the promise of 3-D sound in presenting spatial information.

Vibrotactile systems involve tactual actuators applied to the torso. Research using vibrotactile waist belts indicates that decoding spatial direction information appears intuitive and also requires little or no training. Coding distance information vibrotactilely, however, was unsuccessful (van Erp, van Veen, Jansen, & Dobbins, 2005). Thus, as a unitary source, vibrotactile information does not seem feasible but could be incorporated into a multimedia system to present directional information.

## **Combining Spatial Information Sources**

Based on multiple factors, multimedia navigational aids should have the greatest utility (Agrawala & Stolte, 2001; Frank, 2003; Tomko & Winter, 2006). Designers of such aids, however, should carefully consider the allocation of information to a particular format and the level of detail included in each. Brunyé et al. (2007) examined the interaction in levels of detail between verbal (labeling density) and spatial information for learning a campus environment. They found similar results of generalization (decreased granularity), whether applied to maps or descriptions. The consistency of these findings suggests three general principles for combining map and descriptive information in navigational aids:

- a. More is not better (Schneider & Taylor, 1999) because graphic generalization in maps and spatial generalization in descriptions lead to concomitant reductions in cognitive load, which frees up mental resources to process, store, and recall more information overall.
- b. Designers should appropriately allocate information to different formats.
- c. User goals should be considered in employing combined multimedia aids.

Combining the first two principles would suggest that more is not better, but the two information types can be combined in better and worse ways. Navigational information should be combined to maximize the processing specificity of the working memory slave systems (Baddeley, 1992, 2002). Verbally presented spatial information uses the visuospatial sketchpad (Brunyé & Taylor, 2008b; DeBeni, Pazzaglia, Gyselinck, & Meneghetti, 2005). Thus, too much spatial information, whether verbal or visual, will overload working memory, leading to processing decrements.

Maps present spatial information, both global and local, more efficiently than do descriptions. Verbal information, in contrast, efficiently provides identity information (labels) for landmarks and action-based commands for navigating. As such, navigation systems should use maps for spatial information, which provides the capability for both overview and route-based maps, and use verbal information to label landmarks and describe current and/or upcoming actions (e.g., "Turn left and take the motorway."). Such combinations also have proven useful for supporting individual differences and preferences (Hirtle & Sorrows, 1998).

## **Navigational Goals, Navigational Aids, and Wayfinding**

Navigational goals guide spatial information processing (Curiel & Radvansky, 1998;



Taylor et al., 1999; van Asselen, Firlitschy, & Postma, 2006). Navigational goals influence attention allocation during study and information storage (Brunyé & Taylor, in press). Matching information to such goals can reduce cognitive load, freeing resources for problem solving and reducing navigational errors (Sweller, 1988). Navigational aids, by necessity, need only guide a user to a destination; flexible systems should adapt to the user's goals and existing spatial knowledge. How might navigation systems be designed to account for navigational goals?

The following examples describe a realistic range of navigational goals. Scott just moved to a new city and wants to drive around to get the "lay of the land" so he has a basis for later wayfinding. Tad wants driving information, both directions and time, to arrive promptly at a friend's wedding in a distant city. Holly needs information guiding her efficiently to numerous errand locations in an unknown part of town. All three individuals need information about an unfamiliar environment. However, their travel goals and, consequently, the information needed differ. Getting specific travel directions would not help Scott get the lay of the land, but that is exactly what Tad needs, perhaps with the addition of subgoals such as taking only highways or avoiding toll roads. A "tour guide" system that pointed out salient and/or useful landmarks and roads would facilitate Scott's goal. Holly's goal involves reaching multiple destinations efficiently; she also may have time constraints, such as a store's closing time. Without a good spatial sense of her travel area, she would need either the most efficient route to the multiple locations plotted for her or a plot of all locations on a single map so she could determine an efficient route herself. These users may also develop subgoals during their journeys (e.g., stopping to get gas), and easily inserting these into the travel plans should be in the navigation system design. Anyone who has used one of the current in-vehicle systems no doubt has been annoyed by system commands to "turn around and resume" when pulling off course into a gas station.

Not only do these three individuals have different navigational goals, but the spatial information format that would best meet their goals also differs. Scott's lay-of-the-land goal would best be served with a bird's-eye (survey) map that highlights landmarks of interest to guide his course of exploration. While he is driving, the system could note the current location and verbally point out landmarks of interest and their location relative to Scott's. Furthermore, it may be useful if the map scale changed with the landmark density. Thus, to meet the lay-of-the-land goal, survey maps would be combined with verbal labels and an aural designation of landmark locations.

Tad's single-destination goal could be well served by combining a dynamically updated route or three-quarter-view map, action commands at decision points, and estimates of remaining trip time. Holly's multiple-destination goal would need to combine the two formats subserving the lay-of-the-land and the single-destination goals. The survey map would highlight destinations and their relative locations, and the dynamic route map with action commands would guide travel between destinations. Thus, across these three navigational goals, spatial and verbal information would be combined differently to best meet individual goals.

In addition to navigational goals, individual preferences in a representational format for spatial information affect spatial processing. Pazzaglia and DeBeni (2001) found an interaction in wayfinding performance between spatial preference (high-survey vs. landmark-centered preference) and information format (map vs. description). This interaction

suggested that individuals with a high-survey preference more successfully found their way through the environment when equipped with a map, whereas those with landmark-centered preferences had better success with spatial descriptions. This finding suggests that navigation systems also should account for spatial information preferences.

In summary, cognitive research points to benefits for combining verbal and visuospatial information in navigation systems and provides loose guidelines for considering how best to do so. Spatial information, whether in verbal or spatial format, requires visuospatial processing, whereas landmark identity information—whether in pictorial or label form—requires verbal processing. Furthermore, navigational goals and individual preferences for representing spatial information interact with how information is presented to predict wayfinding success. The most successful navigation system should incorporate these factors into its design.

In the next three sections, we discuss three specific and diverse navigation systems: one focused on in-vehicle ground transportation, one on aviation navigation, and the third on endoscopic surgical navigation.

## IN-VEHICLE NAVIGATION SYSTEMS

In basic terms, navigation involves goal-directed route planning and the execution of movement. In-vehicle navigation systems pose alternatives to the former process by offering increasingly accurate and user-friendly integrated and commercial off-the-shelf (COTS) devices that plan routes and convey this information to users. These systems are particularly useful when navigators must reach a novel destination, move through an unfamiliar environment, or find new routes to avoid traffic congestion.

Most modern in-vehicle navigation systems are robust, to the extent that they provide accurate and comprehensive spatial information, and also have a number of customizable features. Two primary characteristics of in-vehicle navigation systems are of interest here: usability and utility.

**Usability.** Some researchers have argued that usability is the most important characteristic of in-vehicle navigation systems because the systems can be used without overly detracting from the cognitive resources necessary for driving (Burnett, 2000; Dewar, 1988; French, 1997). Usability in in-vehicle navigation systems involves logical organization of controls and features, easy learning, and no requirement for prolonged attention to displays and interfaces. More than a decade of research has led to several extensive handbooks detailing navigation system human factors guidelines (Japan Automobile Manufacturers Association [JAMA], 2000; Society of Automotive Engineers [SAE], 2000; Stevens, deLancey, Davison, Allen, & Quimby, 1999). Much recent work, however, has demonstrated that such guidelines are not sufficient for developing usable systems, and work is yet required to develop structured and useful human factors principles (Brooks, Nowakowski, & Green, 1999; George, Green, & Fleming, 1996; Green, 1996; Nowakowski, Green, & Tsimhoni, 2003; Nowakowski, Green, & Utsui, 2000).

Some commonly identified usability problems with in-vehicle navigation systems are control and menu organization and appearance, integration of auditory and visual information sources, logical procedures for destination entry, early starting guidance for

route selection, display readability and design, and rerouting because of detours or traffic (Brooks et al., 1999; Nowakowski et al., 2003). Nowakowski and colleagues (2003) presented an evaluative process for assessing vehicle navigation system usability and a comprehensive review of common questions arising from system use, such as, "What does this button do?" and "Recalculating the route? I have not even left the parking lot yet!" Though amusing, such incidents also provide a reliable information source for identifying usability gaps and planning reasonable human factors solutions for these problems. Designers of in-vehicle systems can greatly benefit from targeted HF/E research that develops contemporary best practices; the result of such work is decreasing time to learn and increasing attention to the road.

**Utility.** Logical and user-friendly systems are useful only to the extent that they satisfy user goals. A few primary questions arise: What is the relative utility of these systems compared with that of conventional maps or personal guidance? How can route information be presented to maximize system utility? What is missing from modern systems, and how does this motivate human factors research?

Relative to conventional handheld and electronic maps, turn-by-turn vehicle navigation systems generally provide greater utility for navigation tasks (Brooks et al., 1999), likely because of at least two factors. First, effective navigation systems provide only the necessary and sufficient information for achieving a particular goal (e.g., "Turn left"), whereas conventional maps provide information bound only by the scope and folds of the map and are narrowed by human attention. That is, the system acts to filter out irrelevant information and provide explicit action procedures, which allows a driver to focus on the primary driving task without juggling the steering and map-reading tasks or requiring mental rotation to determine turn directions. Second, most modern conceptualizations of working memory divide the system into verbal and visuospatial resources (e.g., Baddeley, 2002). Turn-by-turn navigation systems with auditory instructions (e.g., "Turn left at Park Avenue") make it possible to allocate visual resources to driving and phonological resources to listening to instructions. Although these systems also present maps, they can be ignored largely in favor of the verbal directions in attention-demanding situations. The result is a convergence between visual experience and auditory instructions, and fewer cognitive resources have to be devoted to a single information source (e.g., Wetherell, 1979).

So what should these instructions contain? Much recent work has identified landmarks as critical components of navigation success. People use salient landmarks when describing routes (Daniel & Denis, 2004; Denis, Michon, & Tom, 2007), prefer visually salient landmarks to be included in routes (Denis et al., 1999; Nowakowski et al., 2003), navigate with greater success when an environment contains noticeable landmarks versus when it does not (Daniel et al., 2003; Foo et al., 2005), and prefer landmark mentions even over street names (Tom & Denis, 2003, 2004). Landmarks are also useful when they are coupled with actions—for instance, anticipating and performing an action ("Turn left") is facilitated when this action is embedded within a visual description ("Turn left at the large red high school"; Denis, 1997). These landmarks are especially useful when they are relevant and salient, presenting a clear challenge for human factors researchers to design processes for identifying and drawing users' attention to such features of an environment (Denis et al., 2007; Janzen, 2006; Nothegger et al., 2004).

What is missing from contemporary in-vehicle navigation systems? In addition to what was mentioned earlier, one frequent problem is related to identifying a starting location and direction for the first path segment of a route (Denis et al., 2007; Green, 1996; Nowakowski et al., 2003). Systems must be designed such that sufficient detail is provided to identify a starting position (street name/s, location), heading (direction), and first path segment (street name, metric distance). An additional problem is the lack of information provided during lengthy path segments that do not require any turning activity on behalf of the user; to the extent that systems are able to present explicit metric information ("Continue for 2.5 miles") or define features along the route ("Continue past the library, through the town center"), users will show greater navigation success and report higher levels of anticipation and satisfaction with the instructions (Denis et al., 2007). Navigators also prefer to be able to adequately anticipate and prepare for upcoming turns; this finding supports early work demonstrating the utility of "preinformation" in route guidance (Burnett & Parkes, 1993).

## In-Vehicle Navigation Systems and Cognitive Maps

As in-vehicle navigation systems develop in correspondence with demands set forth by usability and utility evaluations, they are likely to lose their value in helping users develop comprehensive spatial memories. It is clear that there are several distinctions between best practices in a navigation sense and the practices that are likely to facilitate cognitive map development.

Modern in-vehicle systems are becoming more advanced and congruent with navigation demands: They use track-up maps that rotate in correspondence with the vehicle direction, display local three-quarter views as a decision point is reached and survey maps when these decision points are distant, provide details that are necessary only for the navigation task, and are customizable to a user's needs as opposed to their cognitive capabilities and limitations. These characteristics are clearly contrary to many of the findings of research conducted with map and description learning and the optimal presentation characteristics in cognitive map development. Indeed, much recent work has demonstrated the validity of early stimulus-response theory in explaining basic guided locomotion through an environment in the absence of higher-order representation (Hull, 1932; Hull & Spence, 1938; Thorndike, 1903, 1919). It is not surprising, therefore, that such simple-action landmark instructions have been fundamental in contemporary navigation system design (Klippel, 2003; Klippel et al., 2005). Restricting human information processing to such sources, however, may limit people's ability to form cognitive maps that can be recruited when navigation is unaided.

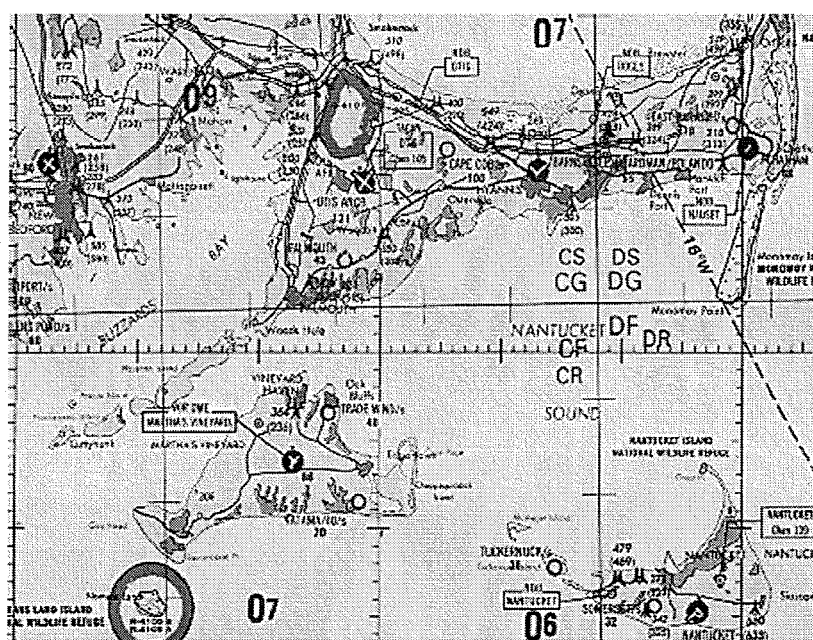
As in-vehicle systems become more commonplace and useful in aiding navigation tasks, users themselves will rely more on these devices to compensate for impoverished cognitive maps. In an era of information accessibility and accuracy, this may not be problematic—but don't throw away the paper maps just yet. When systems fail or present inaccurate information, a user might realize their advantages. Indeed, overreliance on such systems can produce what has been termed *mindlessness*—resulting in navigation failure when systems fail (e.g., Parush, Ahuvia, & Erev, 2007).

## AVIATION NAVIGATION SYSTEMS

In-vehicle navigation systems are a work in progress, but aviation navigation systems have benefited from decades of human factors research, focused engineering to leverage technological advances, and lessons learned from aircraft mishaps. Aircraft navigation systems have evolved through industry-government collaborations to ensure they match operational standards and take into account technical feasibility and safety. Pilot input has improved instrument functionality by reducing cockpit workload (e.g., grouping displays by function, placing displays close to the functions they control; Wickens & Carswell, 1995). Notwithstanding the advances engendered by these processes, navigational challenges in aviation remain.

### Approaches to Aircraft Navigation

Pilot navigation relies on the accurate convergence of information from instruments, aeronautical charts (see Figure 1.4), direct views of the environment, and spatial mental representations. Even the best-designed navigation systems cannot circumvent one cognitive challenge in aviation navigation: linking perceptions of the environment (either visually or from instruments) with the navigation system, the aeronautical chart, and the pilot's mental representation of the current location. In other words, how does the information the pilot has at a given moment fit (or not) the overall navigational plan? This cognitive challenge is combined with other challenges unique in aviation, including (a) incorporating the vertical dimension, (b) lack of predefined paths or "roads," (c) influences of differential wind speed and changing air pressure, (d) poor landmark visibility, (e) no symbolic (e.g., street signs) aids, (f) limited fuel availability, and (g) turbulence.



**Figure 1.4.** Visual flight rules (VFR) chart of Cape Cod, Massachusetts, area. Chart source: National Geospatial-Intelligence Agency.

The information a pilot has for navigating depends on which navigational approach is operating. There are two main aviation navigational approaches: visual flight rules (VFR) and instrument flight rules (IFR). VFR navigation, an essential skill for both student pilots and airline captains with 20,000 flight hours, involves flying with visual reference to the horizon and the Earth's surface and garnering current location information directly from the environment. Successful VFR navigation requires an accurate spatial and environmental assessment, a current chart, and the cognitive process of matching landmarks on the ground to those on the chart. As flight proficiency increases, spatial and procedural mental representations develop. With these changes, navigation evolves into wayfinding, and the emphasis shifts from acquiring information directly from the environment to a stronger reliance on technological aids and one's spatial mental representations.

In contrast, with IFR flying, the instrument provides all information the pilot needs to navigate, including a depiction of the horizon, information on the rate of climb and airspeed, and some indication of present position. IFR flying generally occurs with poor weather conditions and/or in airspace above 18,000 feet in appropriately equipped planes.

It is important to note that although the IFR navigation system can be used during VFR flying, the reverse cannot occur. The requirement difference for these two navigation methods means that IFR, compared with VFR, flying requires the pilot to compile different information during navigation.

## Information Integration in Different Navigation Systems

Pilots receive information relevant to navigation from multiple sources, including the environment, navigational instruments, flight instruments, aeronautical charts, and their own spatial mental representations. Successful navigation requires the pilot to integrate these information types, a cognitive task that cannot be completely off-loaded onto even the best navigation system.

To understand how navigation systems might facilitate this cognitive challenge, one must first understand current methods that pilots employ for integrating information during both VFR and IFR flying. At the same time, one must be aware of what has been coined the *paradox of automation*, wherein efforts to increase awareness through automation paradoxically result in less awareness (Uhlarik & Comerford, 2002; Wiener, 1989).

A standard, nonautomated technique used during VFR flying is the "clock to map to ground" technique, which cognitively aids the pilot in matching landmarks on the ground to those on the chart. With this technique, the pilot first plots flight segments on a chart, determining their length, magnetic heading, and appropriate landmarks to determine position. The pilot then calculates a groundspeed using the aircraft's true airspeed corrected for wind conditions, which in turn is used to calculate how long it will take to fly each segment. So, when our pilot flies over the smokestack (designated turn point), she hacks her clock for the next leg (which she has calculated as 12 min, 30 s at a groundspeed of 120 knots on a magnetic heading of 220 deg). Two minutes later (*clock*), she refers to her chart (*map*) and observes she should be flying over a bridge. Looking down (*ground*), she sees a bridge about a half mile ahead, just after the road curves right. In this case, matching her location to the chart requires little cognitive effort because there are no other bridges on that flight leg, and the road depicted on her chart also curves right prior to

the bridge. She now knows where she is and determines that her groundspeed is slightly less than 120 knots because she had a half mile to fly to reach the bridge.

Notable with this technique is the active generation and integration of navigational information by the pilot. Active generation improves information retention and facilitates mental problem solving and rehearsal (Foley & Foley, 2007; Slamecka & Graf, 1978; Wills, Soraci, Chechile, & Taylor, 2000).

"Clock to map to ground" is not foolproof. The pilot must recruit spatial mental representations created during preflight planning and map them onto perceptual properties of the environment (e.g., whether this smokestack is the same one she designated as a turn point; Boy, 1987; Moray, 1996). Through "clock to map to ground," the pilot builds expectations as to the current location, but external factors (e.g., wind speed and direction) may adapt the aircraft's actual location from these expectations (Besnard, Greathead, & Baxter, 2004). Errors can occur when the pilot matches what she perceives in the environment to her expectations (Baxter, Besnard, & Riley, 2007). Although VFR flying is not particularly "instrument heavy," instruments can aid the pilot in determining current position, thereby averting erroneous expectation-based errors (Baxter et al., 2007; Besnard et al., 2004).

Our bridge example, although instructive, is hardly representative of challenges facing VFR pilots in perceptually interpreting environmental input and reconciling this with chart symbology. Although an aircraft flying over Kansas will have the spatial orientation advantage of agricultural section lines running north-south and east-west, there will also be an endless succession of 90-deg T intersections, which are virtually identical from 4,500 feet. In such instances, "clock to map to ground" is vital to a pilot's situation awareness and essential in avoiding getting lost (Baxter et al., 2007).

Can technological advances in instrumentation facilitate the cognitive challenge of mapping between the current view from the cockpit, the chart, and the pilot's expectation of location? In other words, can such advances facilitate situation awareness? *Situation awareness* means the pilot knows and understands the present and future position of the aircraft and is informed by present position, speed, flight path, and environmental variables such as temperature and wind. Overall situation awareness combines spatial, system, and task awareness (Wickens, 2002). Inadequate assessment, understanding, or monitoring of any of these parameters may lead to inappropriate pilot actions (Federal Aviation Administration [FAA], 1996). In fact, evidence from outside the piloting domain indicates that removing landmarks or decreasing landmark salience has had large and detrimental influences on navigation (i.e., Daniel & Denis, 2004; Daniel et al., 2003; Denis, 1991, 1997; Denis et al., 1999; Foo et al., 2005; Schneider & Taylor, 1999; Tom & Denis, 2004). So what can a pilot do?

Casner (2005) examined whether a GPS receiver with a color moving-map display would increase navigational awareness beyond standard "clock to map to ground." Pilots first flew an unfamiliar circuit with 16 checkpoints either with the moving-map display or with standard charts and then flew the same circuit without navigational resources. Pilots rated their navigational awareness as higher with the moving-map display. However, results suggested that the moving-map display did not facilitate long-term situation awareness. Although pilots navigated more accurately with the moving-map display, this accuracy did not carry over to the second circuit. Without navigational resources, the



pilots in the moving-map group navigated significantly less accurately; two were unable to find their way to the starting point. This finding fits observational studies suggesting decreased awareness for tasks assisted by automated systems (Billings, 1997; Uhlarik & Comerford, 2002). As such, incorporating additional technology and automation does not appear to be a viable solution for improving aviation navigation. However, some instrument design features focused not on automation but on perception can help optimize visual search times when pinpointing current location (McDougall, Tyrer, & Folkard, 2006).

The conditions under which IFR flying occurs (poor visibility, above 18,000 feet altitude) necessitate the integration of different information than in VFR flying. As the name suggests, pilots get all navigation information from instruments during IFR flying, but the specific information depends on the type of IFR systems. One taxonomy for IFR navigation systems divides them as either self-contained or externally referenced. Self-contained systems (e.g., inertial navigation system [INS] or inertial reference unit [IRU]) require no external transmission signal to designate position. Starting from a known latitude and longitude, the system calculates present position from direction and speed traveled. That position can be plotted manually on a chart (see Figure 1.4) or electronically incorporated into a navigation display. Externally referenced systems (e.g., nondirectional radio beacon [NDB], VHF omnidirectional range [VOR], instrument landing system [ILS], and GPS) depend on a transmission from a source outside the aircraft.

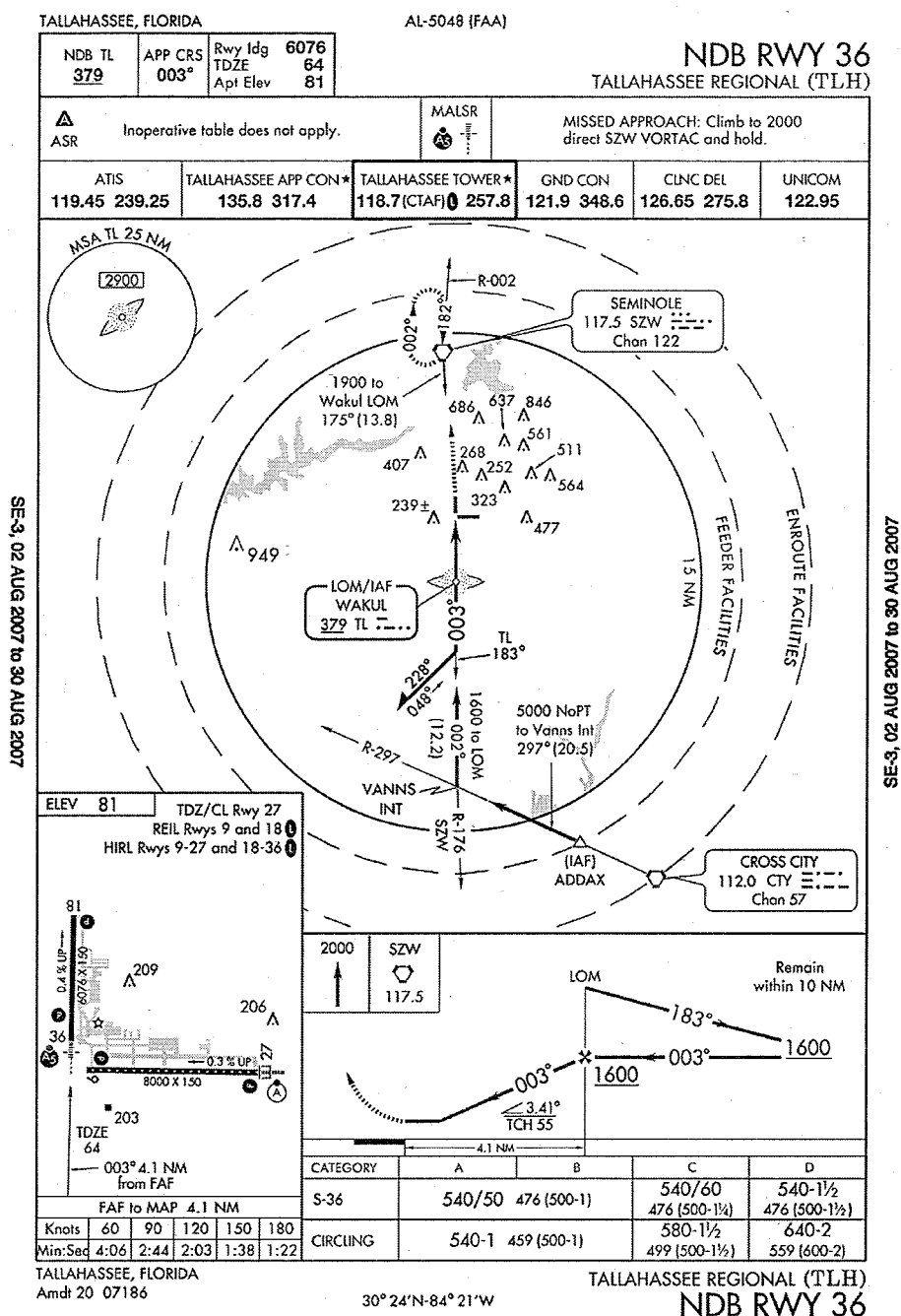
An aircraft's navigation equipment defines its IFR capability, and many are multiply equipped (FAA, 2006). This equipage level also determines the type of information the pilot receives for navigation. Thus, with IFR flying, situation awareness requires information to be integrated both across instruments and to charts (Wickens, 2003).

## **Integrating Visual and Instrument Information With Spatial Mental Models**

Whether you are flying under VFR or IFR, two interrelated spatial tasks are required. First, you need global awareness, which is an understanding of where the aircraft is in relation to geographic references and navigation aids (NAVAIDS; see Figure 1.5 for approach plate with NAVAID information). The next is local guidance: an understanding of how to fly the aircraft to maintain course guidance (Olmos, Lian, & Wickens, 1997). Information integration can present challenges to global awareness, local guidance, or sometimes both (Wickens, 2000).

The following example illustrates global awareness and local guidance and their interaction with vision and instruments in VFR flying. Flying from Centennial Airport south of Denver to Boulder Municipal Airport requires a ground track (local guidance) on a magnetic heading of approximately 318 deg for 33 nautical miles. The global awareness requires maintaining the mountains on the pilot's left (visual). Incorporating the externally referenced NAVAIDS (instrument) into the global awareness means understanding that the Mile High VORTAC will be north at departure and subsequently will be east on approach. This instrument awareness is not required for VFR flying but could enable a pilot to maintain global awareness should she or he be unable to visually determine position. Thus, visually matching landmarks to the chart can be combined with interpreting navigational instruments to verify position and/or recover from disorientation (Wickens, 1999, 2002).





**Figure 1.5.** Chart for nondirectional radio beacon (NDB) instrument approach to Runway 36, Tallahassee, Florida. Chart source: Federal Aviation Administration, National Aeronautical Charting Office.

Incident reports further illustrate the critical importance of combining visual with instrument information and comparing it with a spatial mental representation. On July 29, 2000, an Air New Zealand Boeing 767 approaching Faleolo Airport, Western Samoa, discovered an erroneous rate of descent on the final approach. Had the pilot continued, the airline would have touched down 5.5 miles short of the runway. Instead, when the non-controlling pilot observed terrain and lights higher and closer than he expected, he initiated a go-around, saving the lives of 11 crew and 165 passengers (Civil Aviation

Authority [CAA], 2002). Cognitively coupling these visual cues with instrument readings that also were suspicious for their expected position averted disaster. As the next examples show, some aspects of flying afford the coupling of visual with instrument information, and some do not.

Navigation displays, depending on design, make global awareness or local guidance more salient. North-up displays maintain an external reference frame, thus emphasizing global awareness. In contrast, track-up displays, with their egocentric frame, make local guidance more salient (Harwood & Wickens, 1991). Yet, as our examples suggest, the emphasis on either global awareness or local guidance is not optimal because both are needed. Tlauka et al. (2000) suggested that moderate training with a dual north-up, track-up display can significantly improve overall situation awareness.

In addition to differences in foci on global awareness or local guidance, different IFR navigation systems differentially emphasize spatial processing and procedural processing. One system, the WAKUL, allows the pilot to mentally represent the relative positions of the aircraft, beacon, and runway, which provides information that directly supports cognitive map development. The RNAV, in contrast, requires inferences to plot aircraft location relative to the runway and can be done with complete reliance on procedural instructions. In this latter case, cognitive map development would be a relatively complex process, as indicated by research that demonstrates the relative difficulty of developing comprehensive spatial memories from procedural route-based versus nonprocedural layout-based experiences and descriptions (Brunyé & Taylor, 2008a; Lee & Tversky, 2005; Thorndyke & Hayes-Roth, 1982). It is likely that systems directly conveying allocentric information, such as with the WAKUL system, benefit spatial mental model development and ultimately aid in navigation success.

This discussion of aviation navigation systems provides some insight into the available technology and techniques that are applied to meet the cognitive challenge of matching instrument, chart, and visual information to spatial mental models. Despite the sophistication of modern aircraft, a pilot's ability to establish basic spatial relationships, both on the ground and on the chart, is still essential. On January 23, 2003, a Singapore Airlines Boeing 747 experienced a complete loss of information on the flight deck instrument panels (National Transportation Safety Board [NTSB], 2003). The pilots, with limited stand-by instruments, could troubleshoot and resolve the problem by relying on mental representations of spatial and procedural information. Thus, as with in-vehicle navigation systems, increasing technological sophistication is not always a foolproof solution to the complexities of navigation. In contrast, coupling an accurate and comprehensive mental model of the environment with accurate and well-displayed navigational information can facilitate navigation success. When systems fail or present erroneous data, pilots can flip the switch and rely solely on the knowledge and skills that only experience can provide.

## MEDICAL APPLICATION: ENDOSCOPY

In the 1987 science fiction film *Inner Space*, a miniaturized Lieutenant Tuck Pendleton, played by actor Dennis Quaid, navigates a shrunken craft through the body of Jack Putter, played by Martin Short. Although far-fetched in some ways (e.g., human and object

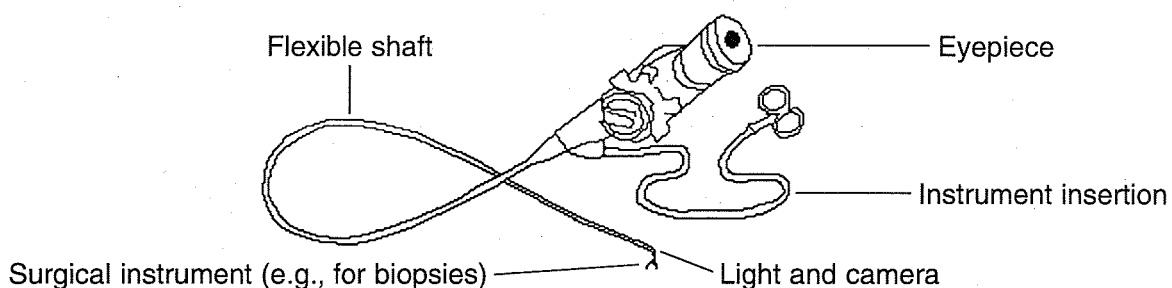
miniaturization), navigation through the human body occurs daily in hospitals via endoscopes. During endoscopic surgery, surgeons insert a shaft through relatively small body incisions. The shafts are instrumented with miniature cameras and surgical instruments (a typical endoscope is shown in Figure 1.6) The surgeon then maneuvers the shafts through the body to complete a particular procedure, whether it be repair, biopsy, or exploration.

From the point of view of navigation, the critical instrument component is the shaft end where the camera, light, and surgical tools can be found. We henceforth refer to this as the *scope end*. Endoscopy has become increasingly popular because it is much less invasive than traditional open surgery, results in less pain, and has faster recovery times and reduced infection rates ("Recommended Practices," 2005). However, one of the most significant causes of error in endoscopic surgery is *disorientation*, here defined as the surgeon's uncertainty of the exact location of the scope end. Navigation difficulty during endoscopy occurs commonly and impedes surgical success (Cao & Milgram, 2000; Holden, Flach, & Donchin, 1999). Thus, issues related to endoscopic navigation provide an interesting application of, and challenge to, understanding cognitive aspects of wayfinding and navigation.

## Challenges to Endoscopic Navigation

Several factors contribute to navigation difficulty during endoscopy, all of which carry interesting implications for mental representations during navigation. First, the viewpoint for navigation (i.e., the end of the endoscope) is removed from that of the surgeon and is displayed at yet a different site, on a video monitor or through an eyepiece, resulting in differences in position and potential differences in orientation. In other words, the surgeon and the scope have different frames of reference, and for successful navigation, the surgeon must adopt the frame of reference of the scope. Adopting an alternative reference frame often involves mental rotation, which is cognitively demanding (Aretz & Wickens, 1992). As in other navigational situations, such as aviation (Aretz, 1991; Gugerty & Brooks, 2004), mismatches in frames of reference degrade navigation success (Rivera & Cao, 2005).

Compounding this difficulty is the fact that the scope end is not directly visible, as it is within the body, and the camera on the scope end itself can be directionally manipulated on multiple axes. Both of these necessitate coordination of visual information (available from a monitor or head-mounted display), haptic information, and the surgeon's spatial mental model.



**Figure 1.6.** A flexible-shaft endoscope. Note that eyepieces are often replaced by video monitors, and shafts range in flexibility from rigid to flexible, depending on the surgical procedure.

Second, scope manipulation challenges increase the surgeon's uncertainty of the scope location. Manipulating the scope can be difficult; the surgeon has four degrees of navigational control, including pushing and pulling or longitudinal control, twisting the scope for a roll, and two controls on the scope end allowing both pitch and yaw (as described in Cao, 2007; Cotton & Williams, 1990). When both the scope shaft and the navigational environment are flexible, such as during colonoscopy, manipulation complexity is compounded. Complications of this degree of flexibility include looping of the endoscope, which occurs at rates reported to be more than 90% (Shah, Saunders, Brooker, & Williams, 2000). In addition, the endoscope lacks tactile feedback and functions with the fulcrum effect (i.e., upward movement by the surgeon results in downward instrument movement). Third, both the navigational region (e.g., colon, sinus cavity) and the endoscopic camera's field of view limit visibility and increase perceptual distortion and visual occlusion. Finally, the landmarks surgeons use as indicators of placement vary across individuals in perceptual salience and/or may be altered or destroyed by disease.

Taken together, all these difficulties yield a high cognitive load for the surgeon (Cao & Milgram, 2000). Consequences of disorientation in endoscopy can be high for patients and include injury (e.g., colon perforation), misdiagnosis, and the inability to complete a necessary procedure. In one study, 71% of bile duct injuries resulted from endoscopic disorientation (Hugh, 2002).

Even experienced surgeons frequently misperceive their scope location or get "lost" during endoscopy, at rates reported as high as around 50% (Cotton & Williams, 1990). Cao (2003) reported that although endoscopic experience contributed to situation awareness (i.e., what is "going on" at the time) during surgery, more experienced endoscopists were as likely as less experienced ones to get lost. This learning curve may result from greater reliance on specific surgical skills and less reliance on general spatial skills (i.e., mental rotation ability), as supported by recent work (Keehner et al., 2004); nevertheless, general spatial skills remain correlated with surgical success (Keehner, Lippa, Montello, Tendick, & Hegarty, 2006). These findings suggest that navigational aids for laparoscopic surgery should focus on both task-specific and general spatial skills.

Cao and Milgram (2000) suggested that getting lost during endoscopy results from both local and global disorientation and that successful procedure completion requires maintained orientation. Yet, "inner space" such as the colon is a much more dynamic environment in which to navigate than is geographic space. This dynamism makes it difficult to make use of an environmental reference frame—in this case, defined by the patient's body axes—further adding to the challenge of maintaining orientation. Thus, endoscopy requires that the surgeon both consult and update his or her spatial mental model more frequently than would someone in a more conventional navigation experience, such as touring a college campus.

## Navigational Aids in Endoscopic Surgery

Because of the factors contributing to endoscopic navigation difficulty, endoscopists frequently must infer the current spatial location of their scope or of a lesion visible by the scope. Some attempts have been made to provide navigational information or aids during surgery. *Fluoroscopy*, which involves a continuous X-ray beam so as to see body parts,

can show the location of the scope end but is time-consuming and exposes the patient to what some feel is unnecessary radiation. Magnetic endoscope imaging, which uses low-density alternating magnetic fields to visualize loop formation during endoscope insertion, has been shown to improve the ability to undo loops but did not improve overall procedure completion time (Saunders, Bell, Williams, Bladen, & Anderson, 1995).

Recently, 3-D navigational technology based on preoperatively acquired magnetic resonance and computed tomography images, in combination with a laparoscopic navigation pointer (LNP), which tracks scope position and allows control of the image display, has shown promise in aiding navigation (Märvik et al., 2004). When using this navigation system, surgeons report better orientation and perceive improved safety. Importantly, the system appears to have relatively high feasibility, in terms of both technology availability and time efficiency. Although self-reports of usefulness often do not match actual performance measures (e.g., Saunders et al., 1995), having a seemingly feasible real-time navigation system during endoscopic surgery deserves further investigation. Indeed, some have advocated for systems-based navigational solutions akin to those adopted in aviation to reduce error and injury (Hugh, 2002).

External navigational aids akin to maps also have been investigated. Cao (2001) showed that navigational aids that provide shape, location, and direction information led to better performance and reduced cognitive load. However, she suggested that having only partial information may be worse than having no information. In a follow-up study to test this prediction, Cao (2007) examined a navigational aid designed to provide only overall shape information about the colon. Such aids have been incorporated into training simulators. Although her untrained participants were more confident in their performance when they had the aid and provided high usefulness ratings for the aid, actual performance did not differ with and without it.

Through experience, endoscopic surgeons develop and fine-tune their spatial mental models of the surgical region. To help surgeons build accurate mental models and improve their endoscopic navigational skills, some have incorporated navigational aids into training regimes and endoscopic simulators. Haluck et al. (2001) designed a virtual reality (VR) trainer focused specifically on improving endoscopic navigation skills. The system gives training with the visuospatial aspects of navigation, particularly the reference frame difference between the surgeon and the instrument, including the angled camera lens. Although designed for training general navigation skill rather than a specific procedure, the system showed good construct validity, with novices making more errors than experts. The findings of Haluck et al. suggest that such VR training systems provide realistic navigation training.

Presumably, different virtual environments could be programmed to help surgeons develop more detailed mental models of body spaces they encounter in their medical specialty. Developers should use caution with increasing the specificity of navigation models, however, to avoid negative transfer in circumstances when internal body spaces are misshapen by disease or injury. That is, the extent to which endoscopists train on canonical body spaces may predict later failures when knowledge must be transferred to novel or altered spaces.

## **Endoscopic Navigation and Spatial Mental Models**

Because navigational aids are unavailable or not feasible or introduce additional risk, endoscopists rely on a combination of their own mental models of the body space and information that is available. Available information may include visual information from the scope (particularly body landmarks), time and presumed distance since a procedure started, and haptic feedback from the instruments and movements required to proceed. Cao, Waxberg, and Smith (2003) found that landmarks and time/distance into the procedure interacted in people's estimates of scope location and that conflicts between these two information sources increased disorientation. Presumably, during a procedure, the surgeon is attempting to incorporate available information with an experience-based mental model to assess the current position. However, the different reference frames that sometimes necessitate mental rotation and perspective taking, the potential for information ambiguity or conflicting information between sources, and the need to update information with a mental model almost continuously combine to create a heavy cognitive load (Cao & Milgram, 2000).

It would seem that to improve endoscopic orientation, a navigational aid akin to an appropriately oriented, dynamically updated you-are-here map could greatly reduce cognitive load, thereby improving orientation as well as surgical outcomes.

## **SPATIAL COGNITION CHALLENGES FOR HUMAN FACTORS OF NAVIGATION SYSTEMS**

In the foregoing sections, we have outlined three dramatically different domains involving wayfinding and navigation. Although the domains and their respective skills clearly differ, the cognitive mechanisms, the way individuals develop and use mental representations, and the factors contributing to disorientation and "getting lost" bear striking similarities. These similarities suggest challenges for innovations in navigation systems and aids, regardless of the domain. In this concluding section, we summarize how spatial cognition research can contribute to the human factors challenges of navigation systems.

How can designers best use principles of spatial cognition and cognitive psychology in navigation systems? As outlined in this chapter, spatial mental representations form when an individual gains spatial knowledge about an environment. This knowledge can be gained through a variety of sources (first-hand experience, maps, descriptions) and is usually obtained in light of a variety of goals (lay of the land, particular destination, multiple destinations). While gaining this knowledge, the individual is faced with cognitive constraints on the amount and type of information that can be processed at once. These constraints arise from the processing dimensions of working memory (Baddeley, 2002) and attentional bottlenecks (Schneider & Taylor, 1999).

These principles can be applied to navigation system design in at least the following ways:

1. Strategically design multimedia systems to present spatial information visually and action and descriptive information verbally (Brunyé, Taylor, & Worboys, 2007). Spatial information, regardless of presentation format or modality, demands resource-competitive working

memory resources (Brunyé & Taylor, 2008b; DeBeni et al., 2005). This principle enables human factors designers to leverage the capabilities of human working memory and at the same time avoid its inherent limitations.

2. Design displays and interfaces to best meet navigational goals. Across individuals, domains, and scenarios, goals can vary widely and alter how people attend to, use, and remember environments (Pazzaglia & Taylor, 2008; Taylor et al., 1999). People also vary in their experience, spatial skills, and preferences. For instance, Shneiderman (1996) presented a case for including generalized route overviews (visually and verbally) prior to delving into route details; these might be particularly convenient for those generally knowledgeable with an area. Empirical work in spatial cognition, data visualization, and human factors presents possibilities for future system design.
3. Design systems to meet spatial information preferences. Individual differences in spatial preferences can have large influences on what types of information people prefer, work best with, and attend to and also how people think about and manipulate represented environments (Pazzaglia & DeBeni, 2001; Pazzaglia & Taylor, 2008). Providing users with the opportunity to self-report preferences about navigation systems can help cater visualizations to individual differences, increase user acceptance, and possibly enhance navigation performance.

It should be clear that navigation systems should be cognitively focused to meet the processing needs of the user. Should the goals be the same, whether for in-vehicle, aviation, or endoscopic navigation? Clearly, navigation systems for different domains have domain-specific constraints in terms of information and displays. For example, a GPS-based system can be used for car or aircraft navigation but would not be suitable for endoscopy. Conversely, the surgeon attempting to biopsy a colonic mass needs information different from that of the pilot attempting an IFR landing, just as they need different skills (see Hegarty et al., 2006). Thus, the navigation system, which may include training as well as real-time navigation, must encompass the domain-specific needs of the user.

At the same time, similarities exist in how people process and represent spatial information across domains and in the factors contributing to disorientation. As such, the basic design principles in presenting spatial information should be similar across these domains but provide users with the flexibility to customize visualizations.

Is there a risk that navigation systems will make users “dumb” because they can rely on the system and no longer need to store spatial memories? The way people use spatial information varies in accordance with individual goals and preferences. Individuals who set out into an environment with the goal of getting the lay of the land may enjoy an enhanced mental representation because of information provided by a navigation system. Someone else, seeking only to find a new restaurant, may retain little information after navigating to his or her destination using a navigation system.

People also vary in their need for cognition (Cacioppo, Petty, & Kao, 1984), suggesting that regardless of navigation goals, some individuals seek out information to retain for future use. Furthermore, current navigation systems are not error proof. As an example, take two different in-vehicle navigation systems programmed for the same destination in a large metropolitan area. Once en route to this destination, one will find many instances during the journey when the systems provide conflicting information.

The navigation systems are clearly only as good as the currency of their map database and the algorithms they use for route finding. If a navigation system is not foolproof, spatial memory and situational awareness while navigating remain a necessity.

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