

Memories of Travel: Dead Reckoning Within the Cognitive Map

Edward H. Cornell and C. Donald Heth

Department of Psychology, University of Alberta, Canada

DRAFT
20 May 2003

Chapter to appear in Allen, G. L. (Ed.), *Remembering where: Advances in understanding spatial memory*. To be published by Lawrence Erlbaum Associates.

Our research is supported by grants from the Natural Sciences and Engineering Research Council and the National Search and Rescue Secretariat of Canada. We thank Michael Snyder and Jack Loomis for their helpful comments.

Memories of Travel: Dead Reckoning Within The Cognitive Map

When Herman Melville reveals the dark obsessions of Captain Ahab's soul, he does so by having Ahab destroy the ship's quadrant and revert to a more elemental form of navigation:

“...Curse thee, thou quadrant!” dashing it to the deck, “no longer will I guide my earthly way by thee; the level ship's compass, and the level dead-reckoning, by log and by line; these shall conduct me, and show me my place on the sea. Aye”

Whatever the allegorical content, the practical consequences of abandoning celestial navigation were immediately apparent to Ahab's doomed crew, who were later to rue his folly and, in the person of Starbuck, ask: “...gropes he not by mere dead reckoning of the error-abounding log?”

Navigation without fixed references and landmarks has been especially intriguing to comparative and cognitive psychologists. The former have tended, like Ahab, to emphasize its simple sufficiency, while the latter, as Starbuck did, worry about its proneness to error. Our everyday experience would seem to favor the active processing of landmarks and reference points. Certainly, our visual facility with objects in spatial frames contrasts sharply with the unease that we feel when we try to traverse a room in the dark. Yet there are compelling examples of species who have somehow managed to beat the odds of the “error-abounding log” and who rely upon navigation systems that apparently mirror the computational steps of the mariner's dead

reckoning. It is apparent that there exist many different systems for navigation both within and across species that may be related to the geometry and ecology of the animal's navigational requirements (Dyer, 1998). In this chapter, we examine the relevance of these systems for human way finding and their implications for the processing of memories of travel.

Definition of the Problem

There are many types of tasks and problems that require spatial information processing, such as the recall of spatial locations, route-planning, and rotation of frames of reference. Our particular concerns in this chapter are those modes of spatial processing that allow an organism to move from a current location to a target or goal. Dyer (1998) has suggested that navigational systems in species are tightly bound to the geometry of the goal. There are, for example, some animals for which the goal may be a shoreline, as in the case of sea turtles that hatch on land but which must reach the ocean before they are captured by predators. Navigation in this case is directed towards a linear feature extended across a two-dimensional surface. There are other cases of navigation in which the space within which navigation occurs is likewise two-dimensional, but the goal is punctate. This latter case differs from the first in that the system must be sufficiently robust to error that the navigator can get within the immediate vicinity of the goal. The cone of headings that will accomplish this task is often quite narrow. For the linear feature geometry, the amount of error that can be tolerated is much larger, since any bearing that is half-plane bounded by the feature will work.

Our emphasis will be on navigational systems that allow an organism to move to or predict the location of a point on a two-dimensional surface. Defined in this way, navigation tasks differ in the way spatial information is made available to the organism. There are generally two elements common to most navigation tasks. First, the organism must perceive a fixed environmental feature. This may be its current location (for example, when a configuration of landmarks is recognized) or it may be the goal itself (for example, when a distant food source produces an odor plume). Establishing the location of a fixed referent point calibrates the organism's representation of its current position; it may also establish the nodes of an organism's cognitive map (Biegler, 2000). That is, for some animals, distinct neural systems represent episodic memories of places within a spatial framework (O'Keefe & Nadel, 1978). Second, the organism is moved to the current location, either under its own power or otherwise, and thereby received information relevant to computing its current displacement. This second process is dynamic and requires that the organism update its current representation of position. There is an analogy with the way shipboard navigators update positional references on a chart on occasions when movement information is logged. However, the mariner's plotting is intermittent and the last estimate of position is represented as the endpoint of a configuration of paths. In contrast, some animals use feedback from motion to calculate position continuously; the history of movements may not be preserved when position is always up-to-date.

In some navigation tasks plotting and calibration are tightly coupled, in a process

known as “piloting” (Gallistel, 1990). Piloting describes the way mariners use sightings of landmarks with known coordinates as they traverse coastal waters (Hutchins, 1995). Piloting provides immediate feedback of movements on calibrated positions through a series of positional fixes. It requires a map with many known reference points, or with frequent positional fixes to interpolate between reference points.

Although piloting might appear to be the predominant type of navigation used by humans, we suggest that it must often be supplemented by other forms. People commonly venture into novel territory, and their frequent shifts of attention might disrupt the cycle of positional fixes that underlie piloting. A good example is children who are expanding their home range (Cornell, Hadley, Sterling, Chan & Boechler, 2001). As they explore new places, they encounter large gaps in their knowledge of landmarks, sometimes under conditions in which other factors (e.g., city traffic) place strong demands on their attention. In such cases, knowledge of position must be estimated through other forms of navigation. Two such methods are known as *dead reckoning* and *path integration*. In each of these modes, sensations of movements may be monitored for long periods without calibration against known landmarks. Because they stand in contradistinction to piloting, dead reckoning and path integration have usually been treated as synonymous. However, we feel that it is useful to consider them as different forms of non-piloting navigation.

Dead Reckoning and Path Integration

Melville may have delighted in the use of “dead” reckoning as a metaphor for

Ahab's decision, but, as many authors have pointed out, the term may derive from "deduced reckoning"—the steps by which a navigator can calculate direction and distance from experiences and observations along the route. Although now superceded by modern modes of navigation, it is a skill still useful to mariners and aircraft pilots. Burch (1986) provides a modern and readable account of the techniques that dead reckoning comprises. At heart, the navigator must be able to calculate speed, time, and direction of travel and, Burch stresses, be able to estimate the error associated with each of these. The latter is especially important, because navigation by dead reckoning is inherently error-prone and must be appropriately recalibrated. Estimates of positional error guide the navigator in determining when other means are necessary to fix a location, or when other heuristics for finding the goal must be used.

For example, a mariner using dead reckoning will need to estimate distance. On the open sea, the mariner cannot directly measure the distance from a location in the morning to a location at day's end. Consequently, estimates of distance are normally performed by sampling speed. Traditionally, a line is knotted at regular intervals, attached to a chip of wood, and cast overboard. As the line plays out, the mariner counts the number of knots passing into the water during a specified period of time. These observations are combined to obtain speed. At the end of the day, the navigator must decide how this estimate characterizes the vessel's speed during the day. If, for example, wind and current are judged to have yielded steady progress for a twelve-hour period, the obtained speed is multiplied by twelve hours to provide an estimate of distance during

that interval.

Notice in this example that daily distance is derived from two estimates, each of which can contain error. There is the risk that the measurement operation was performed during unique circumstances of travel, resulting in *sampling error* of daily speed. In addition, the speed obtained during the sampled period may itself reflect two sources of *measurement error*: the knots along the line might not have the right spacing, or the interval of time during which they're counted might be wrong. The astute navigator will sample speed regularly in uneven seas and factor variability into the final estimate. Error in the final estimate of speed is equal to the square root of the sum of the sampled estimates squared. The art of dead reckoning therefore consists of not only of procedural expertise, but also of judgment concerning relative contributions to error.

Closely related to the procedure of dead reckoning is path integration. In principle, it is possible to compute a location by integrating directed velocity over time (Mittelstaedt & Mittelstaedt, 1982). A navigator may sense velocity by the flow of visual patterns, the feel of the wind, the fading of sounds, or other means, especially vestibular sensations of acceleration; the resulting changes in position cumulate in a process similar to the mathematical operation of integration. When the information for path integration comes from internal sensations of movement (proprioception), the process is called inertial path integration. When the information comes from the changes in flow of external events, such as textures, the process is called noninertial path integration.

The result of path integration is conceptualized to be a probabilistic variable that

encodes both distance and direction to some reference point. A good example of this approach is the model proposed by Fujita, Loomis, Klatzky, and Golledge (1990), in which movements by an organism produce changes to a vector in a history-free manner. Specifically, location along a path is represented by the instantaneous value of this vector, without reference to its previous values. Direction and distance from the last point of calibration are given by direct readout of the vector. Trowbridge (1913) described a similar idea in describing how an animal, having no knowledge of the points of the compass or of the extent of the world, could find its way home:

In the case of insects, birds, mammals, etc., which orient themselves dominantly, it is as if the living creature were attached to its home by one very strong elastic thread of definite length. Hence, in this case, all changes of position of the creatures can be referred at any moment, to definite distances and angles, forming a simple trigonometric figure which gives the direction to home. (p. 890, Trowbridge, 1913).

A key feature of path integration is that calibration in reference to external landmarks does not occur continuously as in the case of piloting. Instead, calibration typically occurs after significant events along a path. For example, Collett and Collett (2000) trained desert ants of the species *Cataglyphis fortis* to walk along a channel to a feeder, after which they were shifted to a new location such that the return bearing was clockwise of the outward path. Ants were later tested by being displaced from the feeder to a novel location. Their attempted return path was still shifted clockwise of the outward

bearing; more tellingly, the return path was generally a straight line. Collett and Collett's interpretation of these data is that the ants' representation of where it was located was calibrated only at the feeder and not during travel back to the nest.

Dead reckoning is likewise a navigation process where calibration usually occurs at significant path nodes. However, the etymology of the term suggests a useful distinction from path integration. In contrast to the latter, dead reckoning is retrospective, implying processes that depend upon representations of previous segments of the path. In humans, this might be apparent in deductive inferences about location based upon remembered configurations of the path. According to this taxonomy, path integration would refer to those models for which information about velocity and acceleration is processed continuously and ahistorically, and represented by state variables of low dimension (e.g., a two-dimensional vector; Loomis, Klatzky, Golledge, Cicinelli, Pellegrino, & Fry, 1993). Dead reckoning, however, would refer to models of navigation in which velocity and time estimates are used retrospectively and at punctate occasions to alter a multidimensional representation of a route or journey (but cf. Loomis, Klatzky, Golledge, & Philbeck, 1999, p. 129). An important part of the representation might be the error associated with specific segments of the route.

The navigation system of *C. fortis* would appear to be one where path integration is an appropriate description. When *C. fortis* foragers are displaced from an outbound path, they are able to establish a return bearing. The accuracy of this bearing does not seem to be affected by where in the outbound journey the displacement occurs (Collett &

Collett, 2000). This would imply a history-free updating characteristic of path integration. In contrast, human navigation seems to fit with models of dead reckoning, because people produce organized memories of their travel.

The Cognitive Mapping of Spatial Memories

Kitchin and Freundshuh (2000) present a good historical review of the uses of the terms ‘cognitive map’ and ‘cognitive mapping’. Our use is based on revival of the terms by behavioral geographers:

Cognitive mapping is a process composed of a series of psychological transformations by which an individual acquires, stores, recalls, and decodes information about the relative locations and attributes of the phenomena in his everyday spatial environment (p. 9, Downs & Stea, 1973).

Information extracted from large-scale external environments and stored in human memory exists in some type of psychological space whose metricity may be unknown (p. 7, Golledge, 1999)

The first statement suggests that cognitive mapping is not an unusual method of processing memories in to and out of a knowledge base, but the information processed is spatial. The second statement reflects that knowledge of the environment may not be uniform; a metric representation of space satisfies certain mathematical axioms, for example, that the quantitative distance between two locations does not depend on the direction of measurement between the two locations. In contrast, people’s sketch maps, distance estimates, proximity rankings and directional judgments indicate an incomplete,

distorted, torn or folded geometry of space, although some well-known areas may be locally Euclidean (Montello, 1989).

The core issues concerning the form and function of cognitive maps have been recently reviewed by Kitchin and Blades (2002). We now know that cognitive maps represent global and local environmental features in a network structure with hierarchical properties. Places may be represented as schemas, such as what comes to mind when told that the village of Rosarita is a beach resort. Spatial information may be encoded as image-like units, conceptual propositions, or both, depending upon task demands and individual differences. The survey representations that characterize cartography are a special product of this knowledge base. Survey maps preserve the angle of bearings and the scale of distances between environmental features; the arrangement of symbols for the environmental features is as seen from the overhead perspective.

To summarize, the term 'cognitive map' is theoretically akin to other terms describing the structure of memories, such as 'semantic network', 'mental lexicon' or 'number fact retrieval table'. There are some properties that are particular to the information in the cognitive map, for instance spatial primitives such as distance relations between events (Golledge, 1995). Nevertheless, because it is the product of normal memorial processes, we assume that the cognitive map is derived from associative, sequential, or configural memories. All of these forms of representation may be useful during way finding.

Could we make it back home?

On Trowbridge's account, pulled by its elastic thread, the homeward-bound animal would eventually encounter a familiar region containing "minor reference points", or objects that give a "definite reaction" to the home (p. 890, Trowbridge, 1913). It is easy to see the prescience of this two-process description. The elastic thread is the line given by path integration, and the definite reaction is calibration of its location vector based on landmarks whose positions are known relative to home.

Of course, the story is more developed now. Some animals may not navigate in the territory close to home by knowing a configuration of several landmarks. There can be recognition of an environment feature that emanates from a unitary site. For example, home may be distinguished by a particular odor. The dispersion of the odorant follows the topography near its source and the prevailing wind. Sensing the concentration of the odorant thus allows for *beacon homing*, with minimal need to represent the location of objects in the neighborhood (Gallistel, 1990).

The foremost path integrator, *C. fortis*, shows limited knowledge of the features around its nest (Burkhalter, 1972). If an ant is trapped immediately after emerging from its nest and placed on the terrain a short distance away, it searches for home in all directions and wanders for an extraordinary amount of time. Yet, the ants return directly from much farther distances when they themselves have traveled away from the nest (Wehner & Srinivasan, 1981).

When researchers move foraging ants after they have traveled to a distant feeding

station, the ants return as if they are heading for home from their last self-determined location. Their return is linear up to a distance where they should have encountered their nest, then their path changes to a loopy search. Wehner and Srinivisan (1981) show that the onset and pattern for the search for home are the result of the ant's mechanisms for computing its displacement. There is little evidence that the ant recognizes its neighborhood, but presumably it recognizes its doorstep.

Given the remarkable path integration by the desert ant, could humans do as well? Blindfolded, ears covered, nose clothespinned and led on a distant foraging expedition, could we return to our doorstep via the most direct possible route? Although our intuitions say no, we shall consider that people may use different cognitive processes to find their way when normal environmental input is restricted. We believe most human solutions are best described as dead reckoning. As we noted above, the term suggests that problems in orientation and navigation can be solved by a variety of methods. Some heuristics for dead reckoning may not involve computation of metric information whereas path integration is associated with the sensing and continuous mathematical integration of linear and rotary velocities or the double integration of accelerations.

In humans, the *proprioceptive system* provides a variety of information that could be integrated to provide a record of translation and rotation relative to the start of a path. The proprioceptive system can be considered to include the vestibular and kinesthetic sense systems as well as representations of efferent commands (Geldard, 1972; Klatzky, Loomis, Golledge, Cicinelli, Doherty, & Pellegrino, 1990). The vestibular sense system

includes mechanisms for registering acceleration and position relative to gravity. The kinesthetic sense system includes mechanisms for registering the movements of joints, muscle and skin. Efferent commands are represented as intentions or preparation of the motor system preceding movement.

Path integration and dead reckoning both operate on feedback from proprioception, although processes of dead reckoning allow for occasional rather than continuous sampling of feedback. Hence, memories of movement and patterns of movement are often important for humans to deduce their bearings. To resolve questions about the representation of self-movement and the accuracy of human dead reckoning, we need to consider what constitutes systematic performance.

Indications of Nonrandom Spatial Performance

Etienne, Berlie, Georgakopoulos and Maurer (1998) summarize evidence that arthropods and mammals show an intriguing systematic bias when returning from an L-shaped outbound journey. In the examples they illustrate (see Figure 1), all species made an inbound error by overcompensating the rotation on the outbound path. Etienne et al. suggest that the systematic bias is owing to the way path integration is computed. Specifically, they favor an iterative mathematical algorithm that describes homing behavior by ants (Müller & Wehner, 1994). The algorithm serves to scale down successive angular deviations between the ant's steps as a function of the distance that the ant has moved away from its nest. Because the computation of mean direction of travel is differentially weighted by the distance traveled, the algorithm is an approximation of path

integration by trigonometry. However, there is evidence that human performance may be more variable (Sholl, 1989; Loomis et al. 1993; Riecke et al. 2002, Kearns, Warren, Duchon, & Tarr, 2002).

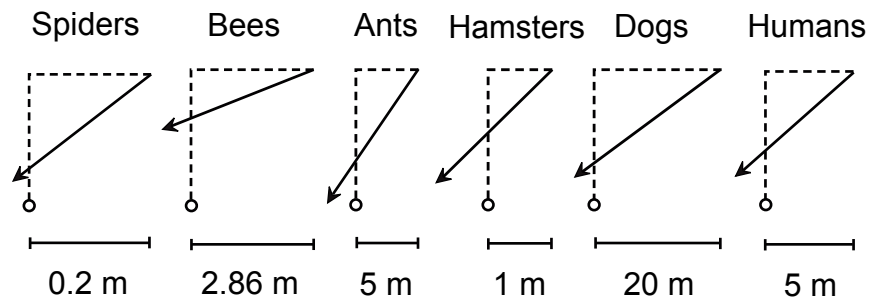


Figure 1. Triangle completion performance by arthropods and mammals (redrawn from Etienne, Berlie, Georgakopoulos & Maurer, 1998). The animal's point of departure is illustrated as an open circle and the two legs of its outbound path are illustrated as dashed lines. The animals returned in the direction illustrated by the darker arrowed line.

Although the algorithm describes the systematic biases illustrated in Figure 1, there may be a variety of mechanisms that produce the same behavior. Notice that overcompensation, or more turning inbound than was done on the outbound travel, results in an inbound path that intercepts the earlier portion of the outbound path. The bias returns the animal to territory that it may be familiar with. For example, children are known to remember the beginning better than the middle portions of new outdoor routes (primacy effects; Cornell, Heth, Kneubuhler & Sehgal, 1996). If children encounter portions of a route after taking a shortcut, they are likely to recognize landmarks or paths that are associated with returning along the route (Cornell, Heth, & Alberts, 1994). They would be in unfamiliar territory if they miss the outbound route by undershooting their turn at the onset of their shortcut. Animals who rely on their own scent trails would also benefit from the bias illustrated in Figure 1. If animals are wandering or searching for

familiar ground, they present more opportunities for predation, meteorological buffeting, or exhaustion. Hence, we would expect that evolutionary factors would act so as to select any mechanism that allows the returning animal to intersect familiar territory.

Innate Representation of Space

Systematic performance in dead reckoning is philosophically interesting. Many modern nativists believe that humans have innately-specified domain-specific representations. They use findings from developmental psychology or neuropsychology and arguments from evolutionary psychology to assert that the human brain is not only innately prespecified for perceptual processes such as registering haptic-kinesthetic flow during movement, but also for higher-level spatial representations such as Euclidean mental maps (Landau, Spelke, & Gleitman, 1984; see Karmiloff-Smith, 2000, for a critique). For example, the study of object localization by a blind girl has led to the interpretation that our spatial knowledge system is structured early in life and is independent of the modality of experience of space (Landau & Spelke, 1985). Her spatial knowledge system was inferred to be a geometric mental map, because after being led along specific paths between objects in a small room, the 34-month-old girl could generate new paths among those same objects. The researchers reported that the girl's movements during these new paths were imperfect; 3 of her 12 test paths ended when she lost her bearings and three of her remaining 9 test paths curved toward the wrong object and then curved back toward the correct target. Despite these missteps, the researchers considered her localization to be better than chance, because on most test paths her initial orientation was in the correct direction and the end of

her path fell within a 40° range subtending the target object. However, these criteria for reaching targets 1 to 2 meters away seem liberal. Moreover, the girl's failure to walk direct lines suggests that path integration was not controlling locomotion. Liben (1988) questions whether the methods allow the strong conclusion that the young blind girl knew the angular and distance relations between the objects in the room.

Veering

There may be an important distinction between turning accurately toward an invisible target and walking a straight-line path to that target. People generally veer when they walk, and direct paths may be seen as a performance requirement that leads researchers to underestimate human competence in path integration tasks. The asymmetries of veering and the extent of veering were early issues in the study of geographical orientation, but the study of veer did not reveal much about the role of kinesthetic and vestibular mechanisms in registering movement (Howard & Templeton, 1966). Extrapolations from a recent careful study indicated that blindfolded adults on average veer about 22° when attempting to walk a straight line for 30 meters at normal speed (Klatzky, et al. 1990). Individuals tended to veer in the same direction over successive walks, but veering to right and left occurred equally often over all individuals. Hence, performance deficits owing to veer suggest that humans cannot solely use inertial cues to maintain straight paths across distances we typically travel outdoors (see Figure 2; see also Guth & LaDuke, 1994; 1995).

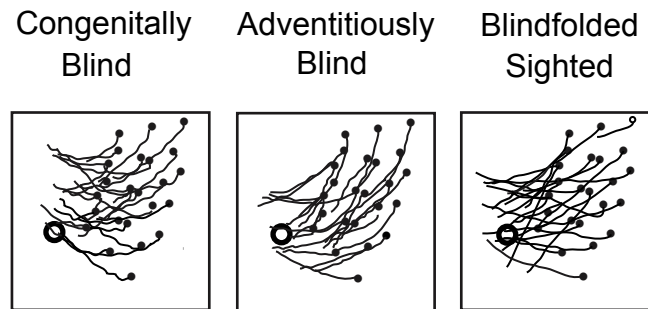


Figure 2. Tracings of return paths by three individuals in triangle completion tasks conducted in a 12 m × 12 m room (redrawn from Loomis, et al. 1993). The person's point of departure for 27 two-legged outbound routes is illustrated as an open circle. The closed circles indicate the ends of the outbound routes and the squiggly lines indicate paths walked during attempted returns to the point of departure. The panels represent performance by the fifth participants within three groups who were deprived of vision.

There are a variety of prospective strategies for correcting error owing to veer. If several travelers are aligned one behind the other, the person at the back of the group can judge the linearity of the column and call forward to the leader to correct to the right or left. The strategy is traditionally used in featureless expanses, as when mushers on snowfields check their line of dogs or camel drivers on deserts shout to the head of the train. Another strategy comes from the sport of orienteering, where runners seek to maintain the most direct line between outdoor check stations. To prevent veer in territory where landmarks can not be identified, runners will alternate the direction taken when encountering barriers, so that if they circumvent a first large boulder by going left, they will circumvent the next large boulder by going right. Perhaps the most mentalistic strategy occurs when experienced hikers imagine a straight-line bearing to their destination at the start of their journey (Jonsson, 2002). Even when distant cues are hidden, the hikers may “steer a course”, or make adjustments to return to the imagined bearing after deviations through travel corridors. Despite these strategies for correcting veer, navigators and way finders seize opportunities to update their position by reference

to geography and landmarks. These observations affirm that people are aware of error and the need to calibrate their movement-based representations.

Tasks in Rooms

Most tasks used to assess path integration abilities are conducted in rooms. Researchers assume that the mechanisms used are the same as those used in larger scale spaces, although a view of a room prior to blindfolding can suggest a geometric shape or regularized framework to situate movement (Werner, 2002). Results indicate that small rooms may be restrictive. A “wall effect” limits the range of errors of some participants (Liben, 1988); they may stop because they are apprehensive of collisions or researchers may interrupt their paths before they encounter a wall. In addition, test rooms are clear of furniture; floor, walls, and ceiling typically provide large, flat surfaces. These are good conditions for echolocation and tactile sensing of reflected ventilation. Researchers have prevented use of auditory cues by fitting participants with occluding headphones. However, studies of visually deprived individuals indicate that participants may also be sensitive to olfactory and tactile cues; these may divert attention from the internal proprioceptive cues that are the basis of inertial path integration. Finally, performance on path integration tasks in rooms is often extrapolated without actually testing whether the obtained error is cumulative over greater distances or determining the conditions that precipitate self-correcting mechanisms while way finding in the greater outdoors.

The scale of the test space is important when considering interpretations of path integration abilities. Typically, adults are asked to reproduce a sequence of path segments

they have walked with guidance, or they are asked to directly walk from the end of their last path segment to the beginning of their walk. Although researchers have devised a variety of revealing path configurations (Klatzky et al. 1990; May & Klatzky, 2000), triangle completion tasks are common. After walking a path segment (leg), turning, then walking a second leg and stopping, a direct return to the origin of the walk is presumed to indicate a form of survey representation of the relations between the legs. Assuming certain criteria for accuracy, performance in the triangle completion task is taken as evidence for a Euclidean representation of metric values of distance and bearing relations. Hence, the length of path segments may determine accuracy of performance and inferences about mechanisms of path integration and the nature of mental representation of space.

For example, the encoding-error model of pathway completion without vision (Fujita, Klatzky, Loomis, Golledge, 1993) assumes that uncertainty about the distances of paths is resolved with a working solution. The distance of a path segment is encoded as a compromise between an uncertain actual value and the mean of presented values. The encoding results in people overestimating small distances and underestimating large ones, an error of regression to the mean (Stevens & Greenbaum, 1966). Notice that calculation of the mean of experienced values requires that people have memories of the distances of path segments they have completed at the time they encode the distance of the most recent path segment. In rooms, people may easily retrieve and summarize path memories after being led through a short series of segments of 2, 4, or 6 meters length. However,

paths in large-scale natural environments typically take more time to traverse and do not include systematic variation in lengths. Estimation may be biased toward memories of early path segments (Anderson, 1981). Under natural conditions, people may use a variety of heuristics to estimate distances that do not rely on a mean value (Hirtle & Mascolo, 1991).

As we shall see, studies with path segments of 2 to 18 meters length indicate that humans can be systematic in processing feedback from locomotion to solve pathway completion tasks. However, these studies indicate a mechanism different than homing based on continuous metric calculations.

Homing

Homing is travel that follows a vector to the point of origin of travel. Homing can be accomplished by piloting or nonpiloting navigation. After finding a morsel, the desert ant provides evidence of a homing vector when it turns and attempts a straight-line return to its nest. Several analyses suggest that the homing vector can be the result of automatic processing of locomotor feedback. Self-velocity and turning can provide input for trigonometric calculation of the distance and bearing of the point of origin (Mittelstaedt & Mittelstaedt, 1982; Fujita, et al. 1993; Biegler, 2000). Bearing within this framework is the angular deviation between the traveler's current heading, or forward direction of travel, and the location of the start of the path. One of the most interesting features of navigation by many animals is that they maintain a vector representation of their way home at all points along their outbound path of travel, yet may be unable to retrace the

paths they have taken from home (Gallistel, 1990; Healy, 1998). Because the homing vector is evident at any place along the animal's outbound path, the process for calculating it must be continuous, or at least occur at distances as short as a footstep. A homing vector is considered by some to be a minimal form of survey representation of space (Loomis et al. 1993), although it is not clear that a homing animal has knowledge of the geometric configuration of its paths as seen from an overhead perspective. Because the animal may show no evidence of memories of its outbound path or landmarks in the neighborhood of its home, the representation of the homing vector in these cases is history free.

There is accumulating evidence that humans do not accomplish path integration by continuous calculation of a homing vector. It can first be noted that sighted people who are blindfolded are not very accurate at returning to the origin of even very simple paths. For example, Klatzky et al. (1990) tested the path completion abilities of blindfolded people after a walk contained within a 10 meter diameter circle. Their mean absolute error turning toward the origin of the walk increased from 22° to 35° as the number of outbound path segments increased from 1 to 3. Mean absolute distance between the endpoint of the participant's return and the origin of the walk also increased as the number of path segments increased from 1 to 3. Klatzky and her colleagues suggested that the increase in errors with path complexity indicated that each segment increased the processing load. This was an interesting interpretation, because there were only preliminary indications that accuracy was related to the representation of segments.

Error could accumulate within a history free mechanism, such as an inexact computational algorithm that discards feedback from locomotion as the homing vector is updated (e.g., Müller & Wehner, 1994).

The cumulative effect of error when sighted humans navigate a large-scale environment without vision is indicated in a recent study by Greidanus (2002). University students were led along a sequence of five connected paths in an unfamiliar suburban neighborhood. The paths ranged between 380-580 meters in length and included 2 to 4 turns. At the end of a path, students were stopped and asked to point to the origin of that path. Students who had walked the paths with total restriction of their vision (occluding goggles) pointed with a mean absolute error of 52° deviation from the actual origin. Students who had walked the paths with normal sight pointed with a mean absolute error of 29° . Students who had walked the paths with their vision restricted to 1 meter around their feet pointed with a mean absolute error of 41° . The performance of the latter group is interesting because they could not see landmarks off the path during their walks. They could see the flow of texture of sidewalks and curbs.

There are now several indications that humans without vision use memories of the outbound path to estimate distance and direction to the origin. Loomis et al. (1993) found that the latency to initiate a return to the origin of a 2- or 3-segment path increased with the complexity of the path. If a homing vector had been continuously updated during the outbound travel, calculation of the vector at the point of return should have required the same time regardless of the path taken to reach that point. The fact that more path

complexity increases latency suggests that subjects are estimating from memories of their travel. The memories may preserve some spatial relations or may be primitives for constructing a representation of the configuration of path segments and turns (Golledge, 1995). The memories are readily available, because Loomis et al. found that human participants could retrace their outbound path on demand, even when the task might have called for a shortcut back to the origin. However, the memories of positional and directional change are not accurate, and as we shall discuss later, are probably encoded with bias toward categorical divisions of space.

Human Travel is a Segmented History

People can easily recall aspects of their movements along paths. Proprioception provides us memories of velocity, acceleration and rotation and our physiology provides us concomitant memories of effort and duration. Several internal events are caused by external events so, for example, walking from a straight to a curved path results in an asymmetry in the efforts of the separate legs and causes a bending of the cupula within the semicircular canals of the inner ear. The perceived changes in the stream of these internal phenomena allow us to segment a sequence of movement, which may be encoded verbally for example as “a few forward steps followed by a hard right”. Whether translated into a verbal code or not, the segmented memories can be the basis of an estimation of the origin of travel (Potegal, 1982; Péruch, Borel, Gaunet, Thinus-Blanc, Magnun & Lacour, 1999; von der Heyde, Riecke, Cunningham, & Bultoff, 2000).

An important experimental approach to understanding the processes humans use

for path integration involves psychophysics and computational modeling (Fujita, Klatzky, Loomis & Golledge, 1993). Psychophysical methods are first used to determine human performance when estimating and reproducing distances and turns (Klatzky, et al. 1990). For example, guided by sliding a hand along a rope, blindfolded participants walked a straight line for 4, 6, 8, 10, or 12 meters. They then estimated the length of the path according to a 2-m standard and reproduced it by walking what they felt to be an equivalent distance from a new starting point. To suppress counting of footsteps, the participant was required to repeat a phrase out loud while following the path. Signed errors indicate under- or overestimation and were calculated by the participant's estimate minus the actual distance. Absolute errors were the magnitude value of the signed error. A hand-held guide was also used to assess turn estimation and reproduction. The participants stood then rotated while sliding their hands along a ring of aluminum with an outside diameter of 94 cm. Clamps were placed on the ring to stop rotation at 60 to 300° on different trials. The participant estimated the amount of turning in terms of a clock face. The researcher then removed the end clamp and the participant attempted to reproduce the rotation. Signed and absolute errors were analyzed.

Performance in these tasks and similar observations by Loomis et al. (1993) served as data to evaluate a model. The model accounts for errors by people deprived of vision who are attempting triangle-completion tasks (Fujita et al. 1993). The model assumes that people in these circumstances have an internal representation of their outbound path that satisfies Euclidean axioms; for example, the length of the legs walked

determines the scale of a triangle that is completed by walking the third leg. In this model, systematic error arises from poor encoding of components of the outbound path rather than an inaccurate computation of a homeward trajectory by use of the axioms. Hence, the success of the model relies on accurate representation of how people encode their movements during travel.

As a start, the model is based on evidence that people make a regression error when they reproduce some turns or distances. That is, the model assumes that people represent the range of turning and distances experienced within some window of recent pathways. When people are asked to reproduce some of the larger turns or walk some of the longer distances, they produce lesser values by ending their movement prematurely. Conversely, when people are asked to reproduce smaller turns and shorter distances, they tend to overshoot. Given the assumption that people encode values of their movements with regression to the mean of recent experiences, the model nicely accounts for data from triangle-completion tasks (Fujita et al. 1993). The model has also been used to infer how people may represent more complex pathways (May & Klatzky, 2000).

The Phenomenology of Movement

The success of this model suggests that it is important to know more about how people perceive and encode movements. For example, both Klatzky et al. (1990) and Loomis et al. (1993) had blindfolded people estimate and reproduce distances after they had walked them while repeating a nonsense phrase. While the repeated vocalization was intended to suppress counting of footsteps, it could have also interfered with other

processes that are normally used to register the duration or effort of walking. The requirement to vocalize repeatedly ensures that participants do not update deliberately during travel and can only estimate when they stop at the end of a path. An estimate at a juncture that considers the path as a whole may be different than a cumulative estimate from subjectively determined episodes of processing.

Certainly, subjective categories are known to be important when people are remembering turns. People are more accurate reproducing turns of 90° , 180° and 270° than turns of 60° , 120° and 300° (Sadalla & Montello, 1989; Klatzky et al. 1990; Loomis et al. 1993). Following the analysis by Howard & Templeton (1966), Sadalla and Montello point out that orthogonal reference axes (e.g., 90° , 180°) are inherent to egocentric orientation. Humans, like many animals with bilateral symmetry, have a front and rear, as determined by the position of systems for sensing events in the path of motion, and arms and legs that can be extended at right angles to the direction of forward motion. Hence, a history of movement may be encoded with reference to the orthogonal planes and axes of the human body.

This encoding is likely to be a process of categorization. Categorization or segmentation is evident when values along a continuous metric dimension, such as the values between 0° and 360° of rotation, are not perceived, remembered, or spoken about as if they only differed in magnitude. Instead, some values along the dimension are special. They are prototypes that serve to organize and represent a category of events. If information about a spatial event is inexactly encoded or only vaguely remembered,

estimates of its value along a physical dimension may be weighted toward a prototypical value (Huttenlocher, Hedges, & Duncan, 1991). For example, using a circular measuring device, people tended to estimate their own angles of rotation as more like 90° than they actually were; turns between 0° and 90° were overestimated and turns between 90° and 180° were underestimated (Sadalla & Montello, 1989). These results suggest that process models of how people reproduce and complete pathways might benefit from an assumption that encoding errors involve regression to prototypes.

In general, we will need to know more about the phenomenology of turning and distance traversal to provide an account of dead reckoning by humans. For example, psychophysical studies of turning have been limited. Early methods sought to isolate how a rotation is perceived and produced from a stand-still, but errors in reproducing turns are different when people experience those turns while walking (Loomis et al. 1993). In addition, we know little of how turns of different radii are estimated or reproduced. The presence of veering suggests that some gradual turns (large radii) are not even perceived as turns. It is possible that when errors and categories of representation of movement are known, the components of human path experience will not be useful for trigonometric calculations. People might use other heuristics to solve the problem of how to head home:

Successful computation might be achieved by an internal scanning process, performed on a spatial image, that derives the direction and distance of the origin. Alternatively, the computation might be a more abstract process that takes as its input nonspatial, even symbolic values of segment lengths and turn

extents (p. 311, Fujita et al. 1993).

Configural Representation of Paths

Memories of human locomotion may be organized to represent both the order of actions and the direction and extent of actions. Since the demonstrations of cognitive maps in animals (Tolman, 1948), psychologists have been particularly intrigued with the notion that the representation of our movements while on the ground is organized to reflect a survey of the territory as if seen from above. However, when people cannot see the environment while walking, they may be preoccupied representing what their internal sensations of movements mean with reference to the horizon. As we shall see, the imagined flow of events along the horizon can provide a dynamic frame of reference for making inferences such as a bearing to a landmark or a short cut home (Rieser, 1999).

An overhead view of the course of travel is a unique perspective. At the least, such a survey of the course of travel would be a configuration, a line figure consisting of path segments and their relationships to one another. If the line figure is closed, as it would be when all of the segments are represented in a triangle completion task, there are geometric properties associated with its shape. Hence, trigonometric computations of a bearing may be based on the episodic memories of two path segments and one turn. The analysis may only have to occur once, when memories are retrieved at the end of the second segment, rather than occurring as a step-by-step or continuous updating during travel. Even without metric computations, shortcuts and detours could be estimated when path segments are remembered and organized as a configuration. A survey representation

allows the viewer to imagine lines directly connecting to points along the figure (Kosslyn, 1980).

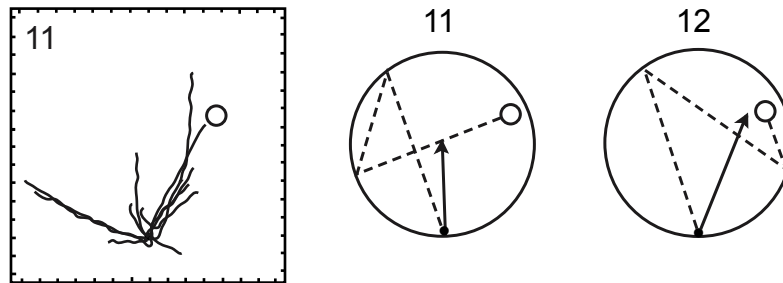


Figure 3. The left panel depicts tracings of return walks by 12 individuals in a path completion problem conducted in a 12 m x 12 m room. (redrawn from Klatzky, et al. 1990). The middle panel summarizes the problem. The point of departure is illustrated as an open circle and the three legs of the outbound path are illustrated as dashed lines. The closed circle indicates the end of the outbound path and the arrowed solid line is the vector representing the average return heading and distance of all 12 participants. The left panel indicates the variability around the average vector in this problem. The right panel illustrates a problem that does not involve a crossing over of outbound paths, although the number of legs, total distance walked, and point of return is similar to those in the middle panel.

One of the first indications that configural properties of paths are important for dead reckoning performance is illustrated in Figure 3 (Klatzky et al. 1990). The middle and right panels illustrate a survey view of two of twelve pathway completion problems conducted within a circular area within a 12 m x 12 m room. The illustrated problems contained three path segments of approximately equal total length at the same point of termination. However, the paths in the middle panel crossed over, forming a closed shape, whereas the paths in the right panel did not. When attempting to return to the origin of the three paths, some blindfolded participants in the problem depicted in the middle panel apparently did not register that they had crossed over the earlier path. As detailed by the tracings in the left panel, they turned at various angles, then walked only short distances. The difficulties on the problem would not be predicted by abstract

computational or homing-vector models (Klatzky et al. 1990). Participant's difficulties could reflect a bias not to represent their path memories as a crossover because none of the other path completion problems included such a topology. This interpretation presumes that participants were monitoring the types of configurations formed by path segments.

People may use heuristics for combining memories of separate turns and distances to estimate a heading. For example, a cumulative record could be that the first turn was almost a complete turnaround to the right and the second turn was almost a complete turnaround to the left. Hikers know this pattern of movement as a switchback and sailors know this pattern as tacking. The opposing turns allow gradual progress forward in the face of resistance. If a participant were familiar with such a sequence, they may know that the origin of their travel is always somewhat behind them as they progress. It is not established that an overhead view of paths of movement is necessary to have this realization.

However, certain tasks may provide evidence that is consistent with spatial inference from a survey representation. For example, it would be interesting to determine the conditions that allow people to draw or recognize a birds-eye view of paths they have walked while deprived of vision. In one study, after leading blindfolded university students along paths in an unfamiliar suburban neighborhood, Greidanus (2002) periodically removed the blindfolds and asked the students to choose a line drawing that best represented an overhead view of their paths. Figure 4 illustrates the configuration of

the actual path and five foils. Patterns of avoidance of foils could indicate that the path had been encoded as a sequence of left-right turns or as having a segment with a gradual curve to the left or right.

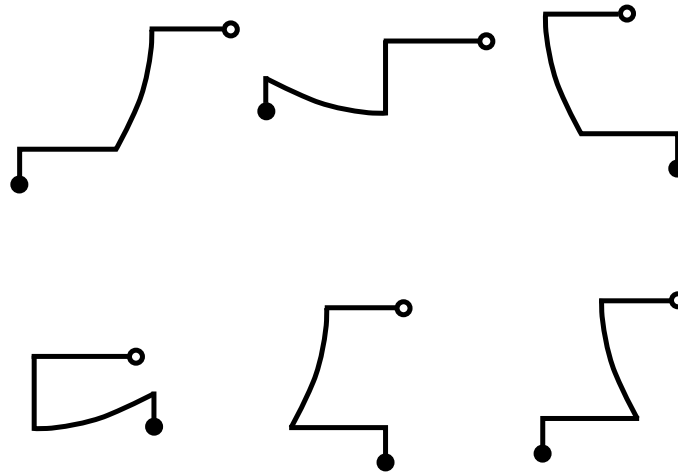


Figure 4. Line drawings representing a possible overhead view of a 458 m walk through an unfamiliar suburban neighborhood (redrawn from Greidanus, 2002). The dark circles indicate the start of the walk, where vision was restricted for some adults. The open circles indicate the end location, where all participants were sighted and asked to select one of these line drawings as a bird's-eye view of their route. The correct configuration is in the upper right.

Blindfolded students chose the configuration representing the actual paths reliably (29% correct). Sighted students did even better (45% correct). None of the students immediately recognized the configuration representing the bird's-eye view, but typically spent minutes eliminating foils on the basis of memories of particular path segments and turns. Interestingly, students whose vision was restricted to views of the path within 1 meter of their feet were also reliably correct (43%). Because during travel these students could not see landmarks that would be useful at the point where they had to identify the configuration of their paths, the results indicate the importance of optic flow for accurate encoding of movements.

Dead Reckoning on the Basis of Optic Flow

Normally, people monitor their position, heading and movements in relation to their environmental surround. They can perceive their travel in terms of changes in the perspective of scenes or the position and faces of objects. There is a natural correlation between the perceived rates and directions of self-movement and the perceived changes in environmental perspectives (Gibson, 1979). Moreover, the correlation holds true as textures of surfaces are seen to flow around and to the sides of the traveler; environmental feedback does not require the presence of discrete landmarks. Sensitivity to changes in optic flow seems particularly useful in situations where only the textures near paths can be seen. For example, a way finder can maintain a straight heading in tall, dense forest by monitoring both the internal sensations of turning and the relative rate of movement of environmental textures on the left and right. There are indications that access to optic flow makes it easier for travelers to structure movements in large-scale space than if they were limited to proprioceptive feedback and memories of efferent motor commands (Reicke, van Veen & Bultoff, 2002; Greidanus, 2002).

Extending these observations, Rieser (1999) has suggested that people register their movements while blindfolded in light of their experience with optic flow under normal viewing conditions. When people are walking without vision, they typically describe their paths in terms of external referents that they remember, such as “parallel to the line of spruce trees”. Evidently, proprioceptive cues associated with self-movement allow blindfolded travelers to imagine how the visual surround would be changing.

People are even capable of imagining that they are in remote territory and then correctly judging their orientation to landmarks in that imagined territory while walking without vision in the laboratory (Rieser, Garing, & Young, 1994). These observations suggest that blindfolded people may solve path completion tasks by situating their actual walking within an imagined familiar environment. They recall memories of scenes. They could, for example, infer a shortcut to the origin of their walk from the bearings of landmarks imagined at the point of return. This inference is of course evidence of Euclidean knowledge of space, but may be principally derived from imagined flow of visual events along the horizon rather than from a representation of path configuration from overhead.

The Plurality of Human Dead Reckoning

Intuitively, human navigation seems based on piloting. The conventional model of human way finding views the way finder as constantly updating positional representations by coordinating external views of landmarks against a cognitive map. This may, indeed, be the modal method by which people find their way. However, there are many cases in which the cognitive map contains important gaps or is absent altogether. Nonpiloting methods, for example, may be particularly important during childhood, when expansion of the individual's home range is dramatic and rapid.

Our review suggests that people do not accomplish nonpiloting navigation by the continuous metric computations that characterize models of animal path integration. People have random and systematic bias in their memories of self-movement. While these errors may be accommodated within models that assume mathematical formalisms

(Fujita et al. 1993), we suggest that people deprived of vision may use some other procedures for making inferences from memories.

For example, some people may update a record of turning by occasionally adding estimates of rotations from their initial heading. Updates could occur at sites where changes in heading occur, in the manner of “My first turn was a bit to the right of my direction of walking from the start and this turn is an extreme left, so I am progressing moderately left of my initial heading.” Updating at the immediate turn would reduce memory load for turning and provide an anchor point for monitoring the relative amount of travel along the new bearing.

We suspect that heuristics operate on route-based phenomenology because people typically describe the environments they walk through as a sequence of events rather than as a configuration (Linde & Labov, 1975; Levelt, 1982). There is no obvious reason why language should lead to descriptions such as “Walk forward about 10 meters, take a hard right, then walk forward a few less steps and stop” rather than descriptions such as “It is an L-shaped route”. As illustrated in the former description, verbal directions and notes indicate that spaces we move within are represented with both metric and categorical information (Taylor, 2000).

Sighted people invariably describe a variety of methods when asked how they solve orienting and way finding tasks in large-scale environments (Hill, 1997; Cornell & Heth, 2000; Cornell, Sorenson, & Mio, 2002). The descriptions involve several levels of analysis of features of landscape, often with clever discernment of details and patterns

that are unique to particular environmental events. People often report more than one strategy to devise a response to pointing and way finding tasks and report different methods for responding at different sites or as tasks progress. Verbal protocols are consistent with models of executive selection of processes to use readily interpretable information, to monitor progress, and to react to anomalous outcomes. These descriptions suggest that normal orienting and way finding, like reading, writing, and many other complex human performances, involve several interactive and compensatory cognitive processes. We suggest that human solutions to dead reckoning without visual input will be found to be similar.

If this is true, group performance on dead reckoning tasks may be an amalgamation of different individual strategies. Averaged data would make it difficult to interpret the processing of memories of segments and turns and discover how people choose certain heuristics to make inferences from these memories (Siegler, 1987). Protocol analyses and task analyses could help to unravel how information is used during dead reckoning (Ericsson & Simon, 1996).

When environmental cues are obscure, one solution seems particularly suited to human cognition. It relies on the ability to recall spatial events to provide a context for travel (Werner & Schmidt, 1999). With our eyes closed, we can imagine that we are in a familiar place or we can reconstruct the immediate environment as it surrounded us before vision was restricted. We slowly begin to walk, and our memories of the patterns of optic flow that accompany self-movement allow us to envision how the view of

landmarks would change. In this solution, we are dead reckoning within the cognitive map.

References

- Anderson, N. H. (1981). *Foundations of information integration theory*. New York: Academic Press.
- Biegler, R. (2000). Possible uses of path integration in animal navigation. *Animal Learning & Behavior*, **28**, 257-277.
- Burch, D. (1986). *Emergency navigation*. Camden, ME: International Marine.
- Burkhalter, A. (1972). Distance measuring as influenced by terrestrial clues in *Cataglyphis bicolor* (Formicidae, Hymenoptera). In R. Wehner (Ed.), *Information processing in the visual system of arthropods* (pp. 303-308). Berlin: Springer-Verlag.
- Collett, T. & Collett, M. (2000). Path integration in insects. *Current Opinion in Neurobiology*, **10**, 757-762.
- Cornell, E. H., Hadley, D. C., Sterling, T. M., Chan, M. A. & Boechler, P. (2001). Adventure as a stimulus for cognitive development. *Journal of Environmental Psychology*, **21**, 219-231.
- Cornell, E. H. & Heth, C. D. (2000). Route learning and wayfinding. In R. Kitchin & S. Freundschuh (Eds.), *Cognitive mapping: Past, present, and future* (pp. 66-83). London: Routledge.
- Cornell, E. H., Heth, C. D. & Alberts, D. M. (1994). Place recognition and way finding by children and adults. *Memory and Cognition*, **22**, 633-643.

- Cornell, E. H., Heth, C. D., Kneubuhler, Y. & Sehgal, S. (1996). Serial position effects in children's route reversal errors: Implications for police search operations. *Applied Cognitive Psychology*, **10**, 301-326.
- Cornell, E. H., Sorenson, A. & Mio, T. (2002) Human sense of direction and way finding performance. *Annals of the American Association of Geographers*, in press.
- Downs, R. M. & Stea, D. (1973). Cognitive maps and spatial behavior: Process and products. In R. Downs & D. Stea (Eds.), *Image and environment: Cognitive mapping and spatial behavior* (pp. 8-26). Chicago: Aldine.
- Dyer, F. C. (1998). Cognitive ecology of navigation. In R. Dukas (Ed.), *Cognitive Ecology* (pp. 201-260). Chicago: University of Chicago Press.
- Ericsson, K. A. & Simon, H. A. (1996). *Protocol analysis: Verbal reports as data*. Cambridge, MA: MIT Press.
- Etienne, A. S., Berlie, J., Georgakopoulos, J. & Maurer, R. (1998). Role of dead reckoning in navigation. In S. Healy (Ed.), *Spatial representation in animals* (pp. 54-68). New York: Oxford University Press.
- Fujita, N., Klatzky, R. L., Loomis, J. M. & Golledge, R. G. (1993). The encoding-error model of pathway completion without vision. *Geographical Analysis*, **25**, 295-314.
- Fujita, N., Lomis, J. M., Klatzky, R. L. & Golledge, R. G. (1990). A minimal representation for dead-reckoning navigation: Updating the homing vector. *Geographical Analysis*, **22**, 326-335.

- Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: MIT Press.
- Geldard, F. A. (1972). *The human senses* (2nd Ed.). New York: John Wiley & Sons.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin Company
- Golledge, R. G. (1995). Primitives of spatial knowledge. In T. Nyerges, D. Mark, R. Laurini, & M. Egenhofer (Eds.), *Cognitive aspects of human-computer interaction for geographic information systems* (pp. 29-44). Dordrecht: Kluwer Academic.
- Golledge, R. G. (1999). Human wayfinding and cognitive maps. In R. Golledge (Ed.), *Wayfinding behavior: Cognitive mapping and other spatial processes* (pp. 5-45). Baltimore: Johns Hopkins.
- Greidanus, E. (2002). *The representation of dead reckoning during a suburban walk*. Unpublished Honor's thesis, University of Alberta, Edmonton, Alberta, Canada.
- Guth, D. & LaDuke, R. (1994). The veering tendency of blind pedestrians: An analysis of the problem and literature review. *Journal of Visual Impairment & Blindness*, **88**, 391-400.
- Guth, D. & LaDuke, R. (1995). Veering by blind pedestrians: Individual differences and their implications for instruction. *Journal of Visual Impairment & Blindness*, **89**, 28-37.
- Healey, S. (1998). (Ed.). *Spatial representation in animals* (pp. 54-68). New York: Oxford University Press.

- Hill, K. (1997). (Ed.). *Managing the lost person incident*. Chantilly, VA: National Association for Search and Rescue.
- Hirtle, S. C. & Mascolo, M. F. (1991). The heuristics of spatial cognition. In K. Hammond & D. Gentner (Eds.), *Proceedings of the Thirteenth Annual Conference of the Cognitive Science Society* (pp. 629-634). Hillsdale, NJ: Erlbaum.
- Howard, I. P. & Templeton, W. B. (1966). *Human spatial orientation*. New York: John Wiley & Sons.
- Hutchins, E. (1995). *Cognition in the wild*. Cambridge, MA: The MIT Press.
- Huttenlocher, J., Hedges, L. V. & Duncan, S. (1991). Categories and particulars: Prototype effects in estimating spatial location. *Psychological Review*, **98**, 352-376.
- Jonsson, E. (2002). *Inner navigation: Why we get lost and how we find our way*. New York: Scribner.
- Karmiloff-Smith, A. (2000). Why babies' brains are not Swiss army knives. In H. Rose & S. Rose (Eds.), *Alas, poor Darwin: Arguments against evolutionary psychology* (pp. 144-156). London: Jonathon Cape.
- Kearns, M. J., Warren, W. H., Duchon, A. P. & Tarr, M. J. (2002). Path integration from optic flow and body senses in a homing task. *Perception*, **31**, 349-374.
- Kitchin, R. & Blades, M. (2002). *The cognition of geographic space*. London: Tauris.

- Kitchin, R. & Freundschuh, S. (2000). Cognitive mapping. In R. Kitchin & S. Freundschuh (Eds.), *Cognitive mapping: Past, present and future* (pp. 1-8). London: Routledge.
- Klatsky, R. L., Loomis, J. M., Golledge, R. G., Cicinelli, J. G., Doherty, S. & Pellegrino, J. W. (1990). Acquisition of route and survey knowledge in the absence of vision. *Journal of Motor Behavior*, **22**, 19-43.
- Kosslyn, S. M. (1980). *Image and mind*. Cambridge, MA: Harvard University Press.
- Landau, B. & Spelke, E. (1985). Spatial knowledge and its manifestations. In H. Wellman (Ed.), *Children's searching: The development of search skill and spatial representation* (pp. 27-52). Hillsdale, NJ: Erlbaum Associates.
- Landau, B., Spelke, E., & Gleitman, L. (1984). Spatial knowledge in a young blind child. *Cognition*, **16**, 225-260.
- Levelt, W. J. M. (1982). Linearization in describing spatial networks. In S. Peters & E. Saarinen (Eds.), *Processes, beliefs, and questions* (pp. 199-220). Dordrecht: Reidel.
- Liben, L. S. (1988). Conceptual issues in the development of spatial cognition. In J. Stiles-Davis, M. Kritchevsky, & U. Bellugi (Eds.), *Spatial cognition: Brain bases and development* (pp. 167-194). Hillsdale, NJ: Erlbaum Associates.
- Linde, C. & Labov, W. (1975). Spatial networks as a site for the study of language and thought. *Language*, **51**, 924-940.

- Loomis, J. M., Klatzky, R. L., Golledge, R. G., Cicinelli, J. G., Pellegrino, J. W. & Fry, P. A. (1993). Nonvisual navigation by blind and sighted: Assessment of path integration ability. *Journal of Experimental Psychology: General*, **122**, 73-91.
- Loomis, J. M., Klatzky, R. L., Golledge, R. G. & Philbeck, J. W. (1999). Human navigation by path integration. In R. Golledge (Ed.), *Wayfinding behavior: Cognitive mapping and other spatial processes* (pp. 125-151). Baltimore: Johns Hopkins.
- May, M. & Klatzky, R. L. (2000). Path integration while ignoring irrelevant movement. *Journal of Experimental Psychology: Learning, Memory and Cognition*, **26**, 169-186.
- Montello, D. R. (1989). The geometry of environmental knowledge. In A. Frank, I Campari & V. Formentini (Eds.), *Theories and methods of spatio-temporal reasoning in geographic space* (pp. 136-152). Lecture Notes in Computer Science No. 639. Berlin: Springer-Verlag.
- Melville, H. (1851). *Moby Dick; or The Whale*. New York: Harper & Brothers.
- Mittelstaedt, H. & Mittelstaedt, M. L. (1982). Homing by path integration. In F Papi & H. Wallraff (Eds.), *Avian navigation* (pp. 290-297). Berlin: Springer.
- Müller, M. & Wehner, R. (1994). The hidden spiral: Systematic search and path integration in desert ants, *Cataglyphis fortis*. *Journal of Comparative Physiology A*, **175**, 525-530.

- O'Keefe, J. & Nadel, L. (1978). *The hippocampus as a cognitive map*. Oxford: Oxford University Press.
- Péruch, P., Borel, L., Gaunet, F., Thinus-Blanc, C., Magnan, J. & Lacour, M. (1999). Spatial performance of unilateral vestibular defective patients in nonvisual versus visual navigation. *Journal of Vestibular Research*, **9**, 37-47.
- Potegal, M. (1982). Vestibular and neostriatal contributions to spatial orientation. In M. Potegal (Ed.), *Spatial abilities: Developmental and physiological foundations* (pp. 361-387). New York: Academic Press.
- Riecke, B. E., van Veen, A. H. C. & Bültoff, H. H. (2002). Visual homing is possible without landmarks: A path integration study in virtual reality. *Presence: Teleoperators and Virtual Environments*, in press
- Rieser, J. J. (1999). Dynamic spatial orientation and the coupling of representation and action. In R. Golledge (Ed.), *Wayfinding behavior: Cognitive mapping and other spatial processes* (pp. 168-190). Baltimore, MD: Johns Hopkins University Press
- Rieser, J. J., Garing, A. E., & Young, M. F. (1994). Imagery, action, and young children's spatial orientation: It's not being there that counts, it's what one has in mind. *Child Development*, **65**, 1262-1278.
- Sadalla, E. K. & Montello, D. R. (1989). Remembering changes in direction. *Environment and Behavior*, **21**, 346-363.

- Sholl, M. J. (1989). The relation between horizontality and rod-and-frame and vestibular navigational performance. *Journal of Experimental Psychology: Learning, Memory & Cognition*, **15**, 110-125.
- Siegler, R. S. (1987). The perils of averaging data over strategies: An example from children's addition. *Journal of Experimental Psychology: General*, **116**, 250-264.
- Stevens, S. S. & Greenbaum, H. B. (1966). Regression effect in psychophysical judgment. *Perception & Psychophysics*, **1**, 439-446.
- Taylor, H. A. (2000). A view of space through language. In R. Kitchin & S. Freundschuh (Eds.), *Cognitive mapping: Past, present and future* (pp. 179-196). London: Routledge.
- Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, **55**, 189-208.
- Trowbridge, C. C. (1913). On fundamental methods of orientation and "imaginary maps". *Science*, **38**, 888-897.
- von der Hyde, M., Riecke, B. E., Cunningham, D. W. & Bühlhoff, H. H. (2000). Humans can extract distance and velocity from vestibular perceived acceleration. *Journal of Cognitive Neuroscience*, **63C**, Abstract 77.
- Werner, S. & Schmidt, K. (1999). Environmental reference systems for large-scale spaces. *Spatial Cognition and Computation*, **1**, 447-473.

- Wehner, R. & Srinivasan, M. V. (1981). Searching behavior of desert ants, genus *Cataglyphis* (Formicidae, Hymenoptera). *Journal of Comparative Physiology*, **142**, 315-338.
- Werner, S. (2002, August). *Integration of spatial reference systems for wayfinding in natural and built environments*. Abstracts of the meetings of the Cognitive Science Association for Interdisciplinary Learning, Hood River, Oregon.