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Place Recognition and Wayfinding: Making Sense of Space

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Place Recognition and Wayfinding: Making Sense of Space

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Abstract: In this paper I examine processes involved in place recognition and wayfinding in the context of spatial knowledge acquisition generally. Recognizing places is seen to be of vital importance in developing a declarative base: wayfinding is viewed as the most common means of acquiring place knowledge. Characteristics of place recognition are examined along with discussion of errors in place cognition and the role that spatial familiarity plays in attaching importance weights to distinguish primary nodes (anchor points) from other places. Wayfinding is characterized as route knowledge acquired via procedural rules. Parameters of wayfinding are discussed in reference to navigation in familiar and unfamiliar environments. The expression of wayfinding in terms of computational process models is examined, and the future role of geographic information systems in such modelling is explored in the penultimate section.

Introduction

Unless we are blind, or completely lost in a pitch-dark night, fog or a blizzard, or for the first time swimming under water in an unknown area, we know that by using vision we can begin to make sense of our surroundings. We look for things that stand out because they are different from their surrounds, or because they have a shape or form or structure that we believe we could recognize again. If nothing catches our attention, we create something—we scratch a mark on the sidewalk or wall, or build a cairn or mound of dirt, anything than can represent to us a sense of location. Once established, this anchors other information processed by our senses. Order can begin replacing chaos. Things we sense now have properties of distance, direction, orientation, proximity, linkage, and association, both with respect to spatial anchors and with regard to each other. We can begin to classify, to cluster, to regionalize, and to impose hierarchies. Where information is sparse, we can create another anchor, establish a relation between this and the initial one (e.g. by establishing a path or base line), and can continue the process of ordering the mass of information bombarding our senses. With such ordering comes security, recognition capability, and, even when all things appear strange and difficult to identify according to our well-established perceptual norms, we can at least identify and use the environment in which we find ourselves.

My purpose in this paper is to discuss some facets of the process of acquiring spatial knowledge. Two important components of this process, recognizing places and finding one's way between places, will be emphasized. To achieve this purpose, I begin by examining different types of spatial knowledge. This is followed by a discussion of place location, recognition, linkage, and choice. The next section examines wayfinding from its elemental spatial perspective, followed by discussion of route learning by humans. The penultimate section examines the integration of these components into a knowledge structure, and briefly points to the role that environments

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[represented as geographic information systems (GISs)] play in the knowledge acquisition process.

Types of Spatial Knowledge

It is usual to distinguish between declarative and procedural knowledge. A person's declarative knowledge consists of the inventory of pieces of information contained in long-term memory. In the spatial domain, this consists of places (such as landmarks or nodes), lines (such as routes, edges, and boundaries), and areas (such as neighborhoods, districts, cities, regions, or countries). Procedural knowledge includes the rules for linking pieces of information into ordered strings. In the spatial domain this is usually taken to include rules of path definition, segment concatenation, associations and relations between points, lines, and areas (e.g. hierarchical ordering), and rules for wayfinding and navigating within a sensed or experienced spatial system.

But some researchers interested in spatial knowledge argue that there is yet another component. Usually called survey or configurational knowledge, this consists of an awareness of configurational properties or layout characteristics of various types of spatial features. Such features are usually not directly sensed, but are inferred from spatial primitives and their derivatives, and are used to infuse meaning into an environment while experiencing it or while thinking about an experience. Thus configurational understanding is achieved by integrating piecemeal information into a comprehensive spatial knowledge system. The existence of this type of knowledge is inferred because of the apparent failure to date of theories based exclusively on declarative and procedural components to account for the nature and development of spatial knowledge.

Behavioral geography and environmental psychology have conventionally assumed that, in the process of acquiring spatial knowledge, individuals pass through stages: from egocentric to allocentric frames of reference and from topological to fully metric comprehension of space (HART and MOORE, 1973; PIAGET and INHELDER, 1967). Critical evaluations of this hypothesis exist [e.g. LIBEN (1982), GÄRLING and GOLLEDGE (1989), and GÄRLING and EVANS (1991)], and no further elaboration of this inferred sequence will be undertaken in this paper. Convention also assumes that there are a few different types of spatial knowledge, usually referred to as landmark, route, and survey. This classification is of importance here and will be discussed further.

Place knowledge, often referred to by the Lynchian term 'landmark knowledge', consists of lists of features perceived to exist in both the natural and built environments. Such features may be mountains, rivers, trees, beaches, buildings, roads, recreational areas, and so on. Attached to each feature is a string of perceived attributes, including things such as location, size or magnitude, identity, time, colour, uniqueness, function, and so on. While Lynch originally used the term 'landmark' to differentiate the features which had outstanding characteristics (such as dominance of visible form or unique size, shape, color, or functional significance), the term has degraded and is now applied generically to known places. New terms, including reference node and choice point, are now applied to those places whose significance is such that many people use them to anchor directions or to act as foci for wayfinding or the regionalizing of information (SADALLA *et al.*, 1980; GOLLEDGE, 1990; GÄRLING *et al.*, 1986). Anchors, landmarks, reference nodes, choice points, and other bits and pieces of place knowledge are absorbed and organized as different environments are experienced.

Most of the information we collect about any given environment is obtained by travelling through it. We may travel through it physically, as by following a path between an origin and a destination in objective reality. We may also travel through an environment by reading a book, by listening to a verbal description, or from viewing image records such as slides, tape, or live television transmission. We may also acquire not just piecemeal but layout information by examining models, maps, areal photos, satellite images, or by simply looking out the window of an airplane as we pass over any given environment. In these latter cases, we appear to do more than simply record information about a long list of different places. We link information in some way, by some set of procedural rules. Such rules allow a person to develop what KUIPERS (1977) calls a 'common sense' understanding of an environment. Knowing that A is linked to C through B allows one to understand how spatial movement can take place and plan for such activity.

Recognizing Places

In the spatial domain 'recognizing' a place means being able to identify its location. In addition to location, occurrences found at particular places have other characteristics, including a name or identity, physical features such as color, shape, size, and so on, a temporal life or episodic interval at which an occurrence occupies a location, and a magnitude or measurement of how much of the occurrence is found at that place. Thus, although place is a dimensionless spatial term, conventionally it is interpreted as a multidimensional phenomenon. Places which are easily identified are said to be 'familiar', but, as GALE *et al.* (1990) and PERON *et al.* (1990) argue, familiarity itself is a complex multidimensional concept. Some people claim familiarity with a place even when they only know its name. Others claim familiarity if they have observed, visited, or passed by the place frequently. Yet others claim familiarity because they can identify an image of it.

Some features stand out from their surroundings. Such places are often regarded as being familiar or well known by a significant number of people. Importance accrues to the place because of this common knowledge. Often designated as landmarks, these places usually provide a significant part of both individual and common cognitive maps of the environment in which they are found. When speaking to others of one's knowledge of a place, these landmarks are referenced most frequently. When directing a stranger to a specific location, a global or superordinate frame of such landmarks dominates general directional and orientation information before specific information found in the immediate neighborhood of a destination is identified.

Given that places can be identified and their features learned, how can such information be stored and used? In answering this question I do not attempt to summarize the neuro-biological or genetic coding literature that speculates on how the brain physically stores information, but instead turn to the literature of geography, geodesy, surveying, and cartography for guidance.

Recording Spatial Information

Places can be located using global or local referencing systems. Since the development of the chronometer and the acceptance of a spherical earth, the most widely accepted global referencing system is via latitude and longitude. In everyday life few use this system or are indeed aware of its essential properties. It is often replaced by a less exact global system that is based on cardinal compass directions. North, south, east, and west are convenient labels to define the edges of a grid that can be superimposed over any surface. Global latitude and longitude measurements can be replaced by more local grid coordinate systems that can be as coarse or as precise as desired. In addition to the coordinate structure, however, a directional component gives a finer existence measure. Having established a location, one could describe another location as being '25 miles southeast of the first'. This establishes a distance and direction so that a vector can be constructed from the first point to the second [Figure 1(a)]. Using an odometer and a compass, the location of the second point can then be determined. The position of the two places are established with respect to each other and with respect to the superordinate grid. The intervening distance is often described as the 'crow-fly' distance and may depart considerably from the 'over-the-road' distance, which is the total number of ground units covered during the journey from the origin to the destination.

Another way of locating a place is to use an offset measure. Assume a possible destination or place of interest is at a location not before visited. Assume further that two landmarks bounding the segment of space containing the desired destination are known. The unknown destination can be located by moving along a path joining the two landmarks until it is possible to take an offset from the main path; the distance of the desired offset and the angle at which it departs from the main route can establish the location of the desired place [Figure 1(b)].

Triangulation is yet another method for establishing the location of a place. A fisherman who finds a productive reef within sight of land may take mechanical or perceptual bearings on three prominent objects. The intersection of the back bearings from the objects can establish location. Similarly, if one

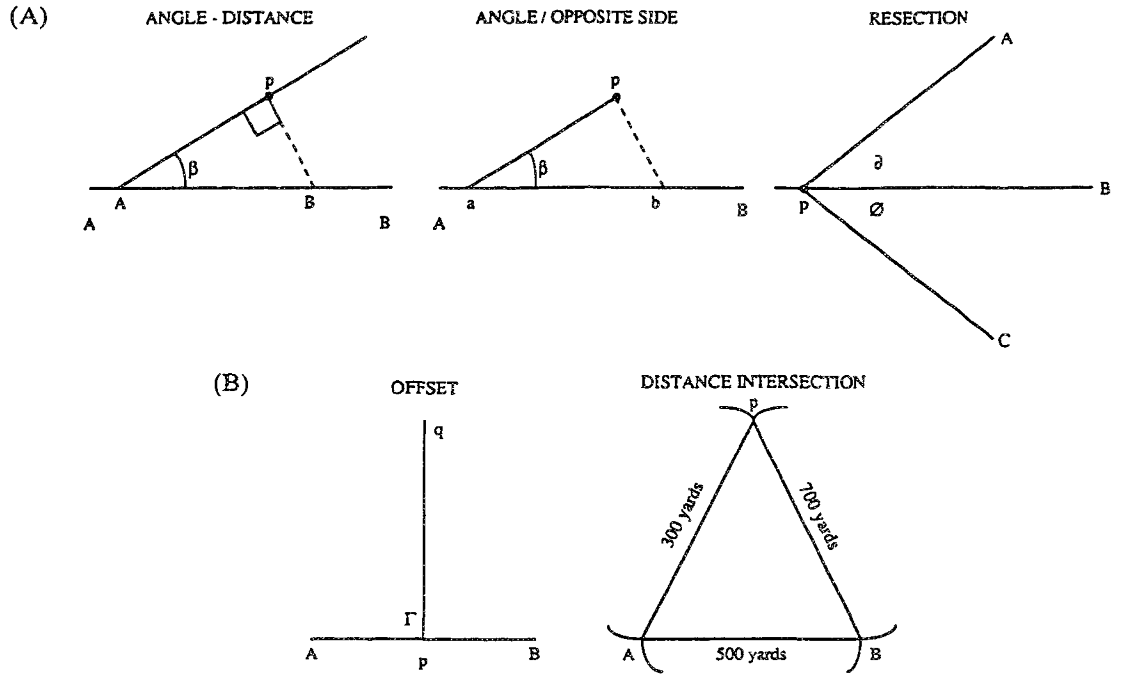

Figure 1. (A) Directional and distance techniques for locating features—direction. (B) directional and distance techniques for locating features—distance.

wishes to find the location of a destination that is known but not seen, and one has no technical assistance, one can replace the precision of the compass with a less exact but convenient method called 'projective convergence'. Here one uses a cognitive map of the environment, by imagining being located at each of three places in turn and pointing at the desired destination. The triangle of error produced by the intersection of the three pointing vectors gives an approximate location for the destination. If the pointing error is large, and the resulting error triangle is also large, calculating the triangle's mean areal center provides a feasible first approximation for the possible location of the destination.

If a destination is out of sight but the distance to it from two or more locations is known, a procedure called trilateration can be used to locate the place. The more accurate the distances, the more precise the locational estimate. In objective reality laser measuring devices allow extremely accurate location with only two locations as long as they are not closely linearly aligned with the possible destination. In the cognitive domain, encoding of both distance and direction are subject to error and it is unwise to use less than three points to try to establish an unknown place's location.

In each of the above cases, I have identified a means for locating a place. In the world of objective reality, precise instruments have been developed to ensure that places can be located with great accuracy (e.g. global positioning systems). In the cognitive domain we must rely on more primitive human abilities. These are the abilities to estimate or reproduce a distance, and to estimate or reproduce an angle, or to use both distance and angle within a particular frame of reference or context. Without a frame of reference, distances and directions can be extremely error-prone. With a good frame of reference, such errors can be substantially reduced. In either the physical or the cognitive domain, places are located using fundamental spatial concepts—location, the interval between locations or distance, and the bearing of one location from another within the superimposed frame of reference.

Example 1: the Errors Associated with Locating Places Using Distances

The data used in this study were obtained from an experiment performed by RICHARDSON (1981). Five subjects were asked to make paired comparison judgments about 19 location cues in a 2¾ × 1¼ mile

Table 1. Average total familiarity, Santa Barbara study*

Cue	Average familiarity
State Street and Highway 101 intersection	8.4
La Cumbre Plaza	7.7
State Street and Cabrillo Boulevard intersection	7.5
State Street and Mission Street intersection	7.3
Santa Barbara Airport	7.3
Mission	7.0
Picadilly Square	7.0
Arlington Theatre	7.0
Fairview Avenue and Hollister Avenue intersection	6.8
Hollister Avenue and Storke Road intersection	6.7
Goleta Beach	6.7
Fairview Shopping Center	6.6
Magic Lantern Theater	6.2
County Court House	6.2
Robinson's Department Store	6.2
Botanical Gardens	6.2
Santa Barbara Harbor	5.9
East Beach	5.8
Biltmore Hotel	5.5
Rob Gym at UCSB	5.5
Isla Vista Beach	5.5
Museum of Natural History	5.4
Bank of America, Isla Vista	5.4
Isla Vista Market	5.3
Ledbetter Beach	5.2
Child's Estate	5.2
Administration Building at UCSB	5.1

*Source: compiled from data collected by author.

neighborhood in Goleta, California. The cues were selected on the basis of extensive questionnaires which were circulated throughout the neighborhood, and they included places such as banks, shops, restaurants, theaters, and so on. The procedure used was the same as that previously used by GOLLEDGE (1974). Subjects were first asked to assign a scale score of 9 to the pair or pairs of cues that were conceived to be the farthest apart, and a score of 1 to the pair or pairs thought to be the closest together. The remaining pairs of cues were then scaled accordingly between 1 and 9. In addition, subjects were instructed to indicate how familiar they were with each place. This was also done on a nine-point scale, with 1 representing no knowledge or familiarity, and 9 indicating that the place was very well known (Table 1).

Having obtained distance estimates, TOBLER's (1978) trilateration procedure, TRILAT, was chosen as a method for obtaining configurations from these subjective proximities. Tobler's original work remains an unpublished manuscript, but there exists a brief description of the algorithm in GOLLEDGE and RUSHTON (1972, pp. 14–17). In its automated form, the trilateration procedure is a two-dimensional metric algorithm that begins with a matrix, **D**, of proximities, d_{ij}, between n points. Given such a matrix, the problem is to find a configuration of the n points defined by x, y coordinates such that $\Sigma(d_{ij} - d^*_{ij})^2$ (where d^*_{ij} represents the distances calculated from these coordinates). GOLLEDGE and RUSHTON (1972) outline the iterative procedure for obtaining a configuration.

Another measure of some interest concerns the metricity of the space represented by the distance estimates. One of the properties of a metric space is that of triangular inequality, i.e. for any triplet of points i, j, k, $d_{ij} + d_{jk} \leq d_{ik}$, where d_{ij} is the distance between points i and j. With a set of 19 cues there are 2907 possible triplets of points. All of the subjects had a very small number of violations of triangular inequality, except for subject 1 who had 230 violations, or 7.9%.

Two additional measures concern distortion and fuzziness. These components of error were previously defined and studied at an aggregate level (GALE, 1982). In this context, individual distortion is defined as the displacement (in Euclidean space for ease of computation) between the objective and subjective location of a cue. Mean distortion is simply the average displacement over all cues for each subject in turn. Fuzziness is defined by the area of the error ellipse associated with each cue.

To compare measures of error across subjects, care must be taken to ensure that all values refer to the same scale. Since the output of the program TRILAT is scaled for illustrative purposes, comparisons of the results from one subject to another are not directly possible. Therefore, the measures were standardized by a series of scale factors.

A final approach involved the contrasting of configurations derived from groups of well-known cues with those derived from groups of lesser known cues. Here, it was possible to uncover relations between familiarity and error. Specifically, both distortion and fuzziness were less for the configurations based on best known places. This was particularly evident with distortion, supported by all cases studied. Similar success was achieved with fuzziness. These results are consistent with the hypothesis that the locations of better known cues are more accurately and more precisely fixed in the cognitive images of the test subjects, thus lending empirical support to the anchor point theory of spatial cognition. However, the sample that was used is a small one, only one urban area was tested, and the method of extracting cue familiarity from the subjects may not have provided the necessary detail for a complete test of the theory.

Example 2: Problems of Locating Places Using Angles

Establishing the location of a place by pointing procedures bypasses the errors associated with distance estimation, but is subject to the errors of angle estimation. In studies with blind and blindfolded sighted individuals, WORCHEL (1951) and KLATZKY *et al.* (1990) have shown that, while people can learn a particular turn angle and reproduce it with considerable accuracy if both the learning and reproduction phase are restricted to rotation of the body, pointing from memory produced errors of up to 35° for a variety of different angles. SIEGEL (1981) and MOAR and CARLETON (1982) have shown that, when people are quite familiar with an environment, their pointing accuracy increases enough to allow projective convergence to give an approximate location for the object being pointed to. This latter technique, however, requires being able to point from a number of different physical locations. When asked to *imagine* that one was at a number of different locations and to draw a vector from each to an unseen destination, the pointing error appears to increase.

Pointing is the externalization of cognized directions. In cognitive science theory generally, it is assumed that, given a declarative knowledge base, and a set of rules for linking bits of that knowledge base to form a series of routes, the opportunity presents itself for recovering a representation of the spatial layout of all the places experienced by learning individual routes. This assumes an ability to integrate lists and procedures into a configurational knowledge structure. The evidence in support of this contention is not strong and has generally failed to thoroughly examine the effect that the pointing error, or the errors involved in reproducing directions, can contribute to configurational distortion. Much of the error already discovered in cognitive maps has not been decomposed into appropriate components. Thus, while locational displacement can be obtained from tasks involving sketch mapping, toy play, or multidimensional scaling analysis of paired proximities, it is not clear as to whether the error so made is a result of incorrect distance estimation, incorrect direction estimation, or a combination of both.

Recent experiments using two partially overlapping routes in a 1 mile × 1 mile square area of Santa Barbara, California (GOLLEDGE *et al.*, 1991), have produced some interesting results as far as pointing error is concerned. In these experiments two partially overlapping routes of different configurations and approximately the same length were learned on a sequence of unidirectional and bidirectional trials. Subjects were given two pointing experiments to conclude a set of tasks [the total experiments and tasks involved are described elsewhere (GOLLEDGE *et al.*, 1991)]. Of importance here is the result of a particular pointing task. In one task, after subjects had learned a route through a relatively unfamiliar environment via exposure to slide sequences, they were shown a series of slides, with one being described as an origin, and the other being described as a place that had to be pointed to. The pointing task was completed on a standard sheet of paper which was said to be oriented in the direction shown by the origin slide. The individual then drew a vector on the sheet of paper equivalent to the direction of the second slide from the origin. In the case of pointing to places on the same route as the origin, some considerable success was achieved, although errors were still usually in the range of 10–25°.

To test the suggestion that layout information could be recovered by integrating knowledge learned on separate routes, a second task was developed in which the subjects were again shown a pair of slides and were asked to imagine that they were standing at the site of and facing in the same direction as the first slide. This time a second slide showed a point on the other route learned in the same environment. Very little success was obtained on this task. Errors ranged from as little as 10° to as much as 170°. Certainly there was little evidence that integration of the two separately learned routes had been achieved, or, if some integration had been achieved, that this resulted in a reasonable understanding of the spatial layout of the task environment. One inference to be drawn from this might be that integration of route knowledge alone does not necessarily produce the type of layout knowledge that is commonly assumed to exist at the survey stage. It also very obviously raises the question of what survey knowledge really is, as well as suggesting that our knowledge of route learning, if the procedures involved in route learning can be used to generate configurational understanding, is not well known.

Recognizing Places: the Concept of Spatial Familiarity

What do we mean when we say we are able to 'recognize' a place, or that we 'know it well'? Such a state is usually taken to mean that we are quite familiar with a place. Familiarity, in this case, is a catch-all term. It may include both spatial and non-spatial components. For example, GALE *et al.* (1990) have suggested there are at least four possible dimensions of familiarity when used in this sense. The first of these indicates an ability to identify a place by recognizing its name or label. Most Americans would say they are quite familiar with the Statue of Liberty by name, just as most French citizens would adopt the same position with respect to the Eiffel Tower. Knowing a place's name, however, carries with it no spatial identity. A second dimension of familiarity might be an ability to recognize a place when shown an image of it. Again, using the previous examples, pictures of the Statue of Liberty and the Eiffel Tower could be readily identified. Such pictures need no locational reference nor background information to assist in such recognition. They stand as images in their own right, distinct from the environments in which they stand. Being familiar with a place by knowing where it is represents yet another dimension of this multidimensional concept. Knowledge of where a cue is can be absolute (e.g. in terms of knowing its coordinates in a global coordinate system) or relative (e.g. knowing where it is in relation to other known places). A fourth dimension of familiarity is interaction frequency. Many places are seen or visited on a regular basis and become integrated into a local knowledge structure. In some cases neither the name nor the function of a place may be known but, because of frequency of exposure when travelling a well-known route, or by knowing the approximate distance or direction of a place from other known places, some combination of visual recognition and locational positioning can be achieved.

At the individual level, the dimensions of identity, visual recognition, and locational accuracy are highly collinear (GALE *et al.*, 1990). It appears that visitation frequency is a reasonable independent indicator of spatial familiarity (as distinct from the more generic concept of familiarity). Spatial familiarity thus implies an ability not only to recognize and locate phenomena, but an ability to relate phenomena to other places contained in a spatial knowledge structure. Locational errors are less for the most highly familiar places. Pointing to highly familiar places apparently produces less error than pointing to less familiar ones. Just as familiarity of a place appears to influence the accuracy of spatial judgments with respect to that place (e.g. interpoint distance judgments, interpoint directional judgments, spatial sequencing, and spatial linkage) so too does it influence the type and amount of error attached to a place upon its inclusion in a cognitive map or internal representation of a layout. The concept is obviously a significant one to include in theories of cognitive mapping and spatial cognition, but, like other concepts discussed in this paper, it is subject as yet to error which is not as yet well specified.

A fundamental axiom of geography is that no two discrete things can occupy the same position in space at the same moment in time. By necessity, things are locationally separated, and linking places often requires moving between them or otherwise connecting them. Wayfinding is such a process. It consists of procedures for searching an environment to find a path that can link an origin and a destination. Navigation is the process of choosing headings, and defining the set of angles, path segments, and speeds of movement needed to locomote over a path. A part of navigation is the designation of choice points where changes of direction or speed are desirable. This need links place recognition and wayfinding: the former is needed to identify origins, destinations, choice points, check points, or general layout information, while the latter is required to specify the path of travel from among all possible connecting links. Although one can differentiate the two processes, they are frequently used synonymously, though navigation is often more focused on the task of reading instruments for guiding a vehicle over a route, while wayfinding frequently refers to the individual movement of living organisms. Recently, research on robotic and automated vehicle guidance has also been couched in wayfinding terms, as has research on computational process models of movement.

Wayfinding

Information about environments usually accumulates while in the process of experiencing them. For the most part, experience implies travel. Regardless of the type of motive power used, travel invariably involves following a route between a specific origin and destination. Much recent effort has gone into building computer models to guide robotic movement or to act as navigational aids for automatic vehicle guidance systems. In both cases, the claim is made that the system being developed is similar to that used in human wayfinding. While the desire has been there, most wayfinding and navigational devices use complex solution algorithms which do not match human wayfinding capabilities or procedures. Criteria such as shortest path or other network-based optimal routing models dominate this literature, most of them requiring an *a priori* map of the existing environment, including the existing routes serving it. Computers examine the map and quickly and expeditiously find a route that satisfies particular maximizing or minimizing criteria built into the relevant path selection algorithm. Given the criteria driving the algorithm, mistakes are rare and optimal paths usually are defined.

But this is not how humans find their way through known or unknown environments. As GÄRLING *et al.* (1987) point out, wayfinders are not generally least effort, short path, or distance minimizers. Given this knowledge, the problem examined in this section concerns the processing of information by humans to allow wayfinding to take place.

The Basic Elements

Finding one's way through an environment implies purposive behavior. In a spatial sense, this requires definition of an origin, the ability to recognize a destination when confronted with it, and the ability to string together path segments and turn angles in an appropriate order to allow the destination to be reached. Information abstracted from the environment and encoded for use in wayfinding includes being able to estimate and reproduce path segment lengths and to be aware of and to be able to reproduce the turn angles between consecutive path segments. While this exercise may be simple for short trips with few segments and turns, as a journey increases in complexity the encoding and storage of distance and turn angle combinations becomes more difficult. Losing one's way usually means either an incorrect encoding of a path segment or turn angle or incorrect decoding of correctly stored information during travel. How often have we been faced with the problem of deciding whether a particular destination is down one turn street or the next? In such cases it is not just the recall and recognition of path sequences and turn angles that allows successful trip completion, but more likely the identification of an environmental cue, either on or off the route being followed, that helps select the next path segment under conditions of uncertainty.

Learning a route involves not only remembering the number of segments and turns, but also the angle of the turns, the length of the segments, critical environmental features at choice points, and other environmental features that occur along or in the vicinity of path segments (e.g. ones that can be seen from the route and used as orientation and locational aids). Thus, when traversing a route, even when a path is followed that was not part of the original learned route, a successful trip can be completed if recognition of a nearby landmark assures the traveller that she/he is at least heading in the 'right direction'. Learning a route, therefore, involves being aware not only of the route segments experienced during a successful trip, but also developing a strategy of recognizing environmental features that allows for compensation of wrong choices when turning or when viewing a landmark from a different angle.

Route Learning in Familiar and Unfamiliar Environments

Over the years a research team at the University of California, Santa Barbara has examined the acquisition of route knowledge over time via repeated learning trials on selected routes within familiar and unfamiliar environments (DOHERTY, 1984; DOHERTY and PELLEGRINO, 1986; DOHERTY *et al.*, 1989; GALE *et al.*, 1990; GOLLEDGE *et al.*, 1991; PELLEGRINO *et al.*, 1990). Each of these studies used a battery of tasks to examine the ability of subjects to recognize scenes that were either found on the routes to be learned or in the same or different neighborhoods.

Two types of scenes were considered—'plots', which were scenes of individual cues such as houses, natural environmental features, or other signs of human occupancy, and 'views', which were extended images of what one might see when looking straight ahead down a route segment. Experiments were conducted both in the field with immediate debriefing in a mobile laboratory following field experience, and in the laboratory where route learning took place by viewing slides or videotapes of a particular route. Recognition tasks were developed which required subjects to be able to determine whether or not a specific plot or view scene was on or off a route or in or out of the neighborhood through which the route extended. In addition, sequencing tasks, again using plots and views, helped determine if the correct ordering of route segments took place, while sketch mapping procedures provided evidence of whether the approximate number of segments, their length, and the turn angles connecting them were appropriately encoded. Other tasks were defined to test whether cues were located cognitively in their correct segments, and whether or not subjects were able to infer proximities between readily identifiable cues when across-segment judgments were made (GALE, 1985; GOLLEDGE *et al.*, 1991).

Most recently, a series of orientation and directional estimation tasks were devised using pointing from imaged locations to other imaged locations to see if encoded route information duplicated the real configuration of learned routes. To examine whether the MOAR and CARLETON (1982) and SIEGEL *et al.* (1984) suggestions that people were able to integrate knowledge obtained from routes into a general knowledge of the layout of an environment can be duplicated, tasks were devised to see how accurately subjects could estimate the orientation and direction of a point of one learned route to a point on a different, but partially overlapping learned route. The lack of success in completing these tasks (GOLLEDGE *et al.*, 1991) runs counter to the route integration hypothesis and appears to suggest that an additional type of knowledge structure—configurational or spatial relational knowledge—develops in the spatial domain.

Segments and Turns

Our past research has tended to confirm the findings of ALLEN (1981, 1985, 1987) and ALLEN and KIRASIC (1985) that route learning usually involves chunking of the routes. These chunks or segments can be sequenced far more effectively than would be the case if one tried to learn the correct sequence of an extremely large number of individual cues that make up each route segment. This chunking hypothesis accounts for the ability to order masses of information into correct sequences. Errors are sometimes made, however, when the turn angle connecting sequences is encoded incorrectly. For example, 90° turns may be encoded as 270° turns, resulting in a 180° switch in route direction. This could result in immediate disorientation and a sense of being lost, even though the balance of information along the route could be encoded correctly and followed accurately. Alternatively, smooth curves may be encoded as continuous straight lines with no change of direction, and non-right-angle turns can be encoded as right angles. Each of these cases may pose no hindrance to the successful completion of a trip through an environment. However, if stored incorrectly in one's cognitive map, attempts to guide other people or to reproduce one's knowledge structure externally for use by other people may result in error or misdirection.

Environmental Complexity

ALLEN (1981) showed that, if the environment was sufficiently differentiated, route learning could take place quickly and efficiently through a segmentation or chunking process. Chunks of the environment that were internally similar, or that were differentiated from other chunks by a significant landmark or other environmental cue (e.g. a change in housing styles, a change in housing density or lot size, an increase in the quantity of neighborhood vegetation, or change from rectilinear to curvilinear street patterns), can provide criteria for the cognitive segmentation process. A given route under these circumstances may proceed without terms for quite a while, but still be chunked as part of the process of classifying environmental information and simplifying it. Alternatively, where the environment is relatively undifferentiated and uniform (as is often the case in some large surburban residential tracts, or in inner-city areas dominated by row houses or sets of uniformly constructed high-rise apartment buildings) it is a much more difficult task to undertake segmentation.

Route Complexity

Conventional wisdom assumes that, as routes increase in length and complexity, the ability to remember and traverse them without some type of aid (e.g. a map) decreases. Reference is frequently made to the magic number 7 ± 2 as being the upper asymptote of route segments that can be learned with relative efficiency and low error.

In one of the first studies combining distance perception with route learning, BRIGGS (1972) showed that cognized route distance remained a power function transform of objective distance regardless of whether the routes were straight or curved, and whether intermediate turns were towards or away from the final destination. Recently, HAYASHI *et al.* (1990) provided clear evidence that, as the number of route segments increased, the perceptual error increased.

The substantive problem with which Briggs was concerned was the influence of environmental structure upon the cognition of distance. The hypothesis put forward was that, for equivalent objective distances between points within an urban environment, cognized distance varies as a function of route complexity between points. In particular, Briggs hypothesized that, for equivalent objective distances, the cognized distance from a common origin point would be greater to locations towards downtown than to places away from downtown; and, secondly, that for pairs of points an equivalent objective distance apart, but linked by routes involving turns or bends, the routes with bends or turns will be cognized as longer and the origin and destination points cognized as farther apart than points linked by a straight route.

Briggs' results generally showed that distances to downtown locations were overestimated relative to those away from downtown. With respect to straight routes against those involving turns, Briggs inferred that a different scale was used by subjects for routes with bends compared to routes as straight lines. This suggested that, along routes with bends, interpoint distances were cognized more as crow-fly distances than as over-the-road distances. This is an interesting conclusion. It appears from this that routes are not encoded simply as concatenations of line segments. Rather the anchoring end-points, and their relative interpoint distances, are perceived more as shortcut or crow-fly distances than as over-the-road distances. Such a finding would tend to support a hypothesis that information learned from routes *could* readily be integrated into a configurational knowledge structure. In such a knowledge structure, the relative position and direction of points from one another establish the positional layout. Over-the-road measures of connectivity are important only for estimating travel time. These results also suggest that travel time and distance are *not mere substitutes for one another*, but reflect two quite different purposes in the construction of cognitive maps. The linking of points in a configuration by straight-line distances helps establish the two-dimensional layout upon which more detailed information can be grafted at will. Thus, when required to travel between an origin and a destination, it could be hypothesized that one first establishes an image of the relative locations of the places, and then attempts to determine a route between them that will satisfy some type of movement criteria (such as minimizing time, maximizing aesthetic value of the journey, or minimizing stress and anxiety). This could help account for the many and varied results which tend to imply that individuals are not minimum-path travellers (when the minimum path is interpreted in terms of route distance measurements). Certainly, envisaging connections between locations as straight lines provides the directional information that over-the-road travel may not.

Returning to a point made earlier in this paper, the use of the crow-fly distance to connect points allows the use of simple triangulation procedures to locate each point—a procedure which over-the-road connectivities do not allow whenever there are bends or turns in the road. It also implies that individuals who know only the time of travel between places may have great difficulty in constructing accurate configurational or layout information. Since it is suspected that many people encode route information in temporal terms, one should not be surprised by results that indicate that people who learn environments by routes are less than precise at locating landmarks in those environments and knowing the approximate directional and distance information of each landmark from others.

Wayfinding Errors

Wayfinding errors can occur in both encoding and decoding information. For example, the incorrect sensing of (forward) speed can result in distance travelled being overestimated or underestimated. Incorrectly integrating velocity to obtain distance travelled on each leg of a multi-segment path can also produce error, which may result in misspecification of the location of a critical choice point or destination. Such errors may also result in improper identification of key landmarks, particularly where little perceptual variation exists—as might be the case in a uniform residential neighborhood.

Incorrectly sensing the role of turn also leads to an encoding error. This may result in incorrectly integrating turn rate when trying to define a new heading, resulting in the incorrect encoding of a turn angle greater or less than a right angle, or encoding smooth gradual curves as straight lines.

Wayfinding errors may also result from using an erroneous or biased representation of an environment as the spatial basis for decision making. Stretched, folded, or incomplete cognitive maps lend themselves to both navigation and wayfinding errors. Here the error may result from incorrectly decoding correctly sensed information (e.g. because of stress, anxiety, brain damage, etc.) or correctly decoding incorrectly sensed information (e.g. as specified above).

Yet another type of wayfinding error can occur if erroneous updating of self-position occurs while navigating. This may result from incorrectly performing the mental trigonometry used to estimate bearing or distance of a target location, or when attempting to solve a shortcutting problem. Humans are notoriously poor path integrators—which is the reason for millennia of experimentation to produce more accurate ways of measuring distance, angle, and speed. The simple fact is that most human travel unassisted by technical aids is error-prone.

In recent experiments using blind and blindfolded sighted individuals, LOOMIS *et al.* (1991) have shown that an increase in route complexity produces an increase in error when subjects are required to learn an incomplete configuration of segments, and then return directly to 'home' using a shortcutting procedure. The different configurations used in these experiments varied from simple right angled triangles to squares, rectangles and quadrilaterals. The most complex route was a crossover in which it was necessary for the traveller to cross an initial leg before returning correctly to the home base.

Computational Process Models of Wayfinding

A variety of computer simulation models—called computational process models (CPMs)—have been developed for navigational purposes [see KUIPERS (1977), GOPAL *et al.* (1989), and LEISER and ZILBERSHATZ (1989), for examples]. LEISER and ZILBERSHATZ (1989) suggest that experience with a large-scale environment is at first unstructured. Although specific environmental cues are recognized and learned, they are not necessarily spatially connected one to another, but simply listed in a declarative structure. With increasing experience, however, routes are learned which connect specific locations. As the relational characteristics between places on and off these routes become recognizable, a survey-type knowledge structure develops. The sequence is similar to that argued by SIEGEL and WHITE (1975) and GOLLEDGE (1977). Once a survey-level knowledge structure is obtained, then geometric relations between points such as crow-fly distances, orientation to frames of reference, and directions between places can be comprehended. They also argue that many people are unwilling to recognize the extent of their environmental knowledge, preferring to develop repetitive travel patterns which confirm the learned anchoring structure of their cognitive map, but which may also inhibit exploration or the search for more efficient connecting routes.

With respect to route knowledge, empirical evidence often contradicts theory. For example, THORNDYKE (1980) and ANDERSON (1982) argue that proceduralization acts on a declarative knowledge base to allow route knowledge to emerge. Proceduralization consists of sets of production rules that can be accessed to fire in the correct sequence to help recall memorized sequences of movement through a particular environment, which in turn allows successful trip completion. There would be no reason to expect proceduralization to work differently depending on the direction travelled between any two points. However, SADALLA *et al.* (1980) showed that distances were perceived differently depending on whether they were to or from a reference node, and SÄISÄ *et al.* (1986) have demonstrated that segment and route length estimates are asymmetric. It is difficult to see how a single set of production rules can handle these asymmetries, just as it is difficult to imagine how production rules could account for the different type of directional and orientation errors that are made in the learning process and that sometimes are part of the final product.

The building of a computational process model based on the simple symmetric hypothesis produces error-free travel along specific routes and is at best an ideal situation or norm from which one can measure departures. Such models may also have difficulty in accounting for distance and directional cognitions where crossing of regional boundaries occurs. GOLLEDGE and SPECTOR (1978) have previously argued that, while travel habits may be repetitive and predictive within a household's activity space, at the fringes of this space and outside it each individual generally has only enough information to reach a given destination from well-known places (i.e. major anchor points); knowledge of the surrounding environment is sparse.

Other models designed to simulate learning of spatial networks have been produced by KUIPERS (1978), McDERMOTT and DAVIS (1983), SMITH *et al.* (1982), and GOPAL *et al.* (1989). The production rules built into such models allow learning to take place on repetitive trials and allow the successful completion of a task. However, the models do not simulate any particular person's natural travel behaviour because of things such as the inability to incorporate asymmetric distances and directions, and the inability to specify on any particular trip the most appropriate criteria that might be selected by a human traveller. Such criteria range from minimizing time of travel, minimizing distance of travel, expending least effort, minimizing stress or anxiety, minimizing the number of turns, maximizing the aesthetic value, minimizing the chance of being lost by taking longer routes via well-known anchor points, and so on. Clear sets of well-authenticated criteria for explaining wayfinding do not exist.

The typical computational process model begins by setting out from an origin without prior knowledge of the network through which a traveller must pass. It is therefore working in an unfamiliar environment, and does not have the access to ancillary tools such as maps or photographs of the area, nor does it know the reference frame of the task environment. All these must be learned. The moving organism does not know what paths or path alternatives it will later encounter, nor whether the initial path that it selects is an efficient or effective start to the linking of a given origin and destination. The basic components of the model, therefore, consist of condition–action pairs which usually take an if–then format. These pairs accumulate consecutively to form the production rule that defines the initial route. In a sense, a production rule for a route segment provides a signpost for selection of the next segment.

Once a simulated traveller has been stimulated to leave an origin, it first proceeds by scanning the adjacent nodes to see if any of these are the destination. If a particular node is the destination, a scan is made to see how many routes can reach that destination. Obviously, to avoid excessive enumeration of all possible routes, some criteria such as least effort, least number of turns, or minimizing the number of segments, need to be used as controlling factors. If an adjacent node is not the destination, a typical process is to select each adjacent node in turn and scan in its vicinity for the destination. This process is repeated and the search space expands uniformly in all directions—if a regular network exists. Irregular searching takes place if the network is incomplete (i.e. not a completely linked graph), or if the distance apart of nearest neighbors increases in some areas while remaining constant or decreasing in others. In this way a computer accumulates information about the entire network.

This comprehensive learning process is quite different to that normally used by humans. The latter do not explore sequentially and successively all areas in the vicinity of every node in the network. Human search space is invariably sectoral and may be guided by even a small piece of information such as a chosen heading: thus, if one hypothesizes the destination is to the north, then eastern, western, and southern nodes are eliminated early in the search process. Once sectoralized, however, a further constrained set of production rules guide segment selection by eliminating turns that appear to direct the traveller away from 'moving in a northerly direction'. Later as more information about the general layout of the environment becomes known, this orientation rule may be violated if the traveller finds that an effective route can be determined by first moving in the nonprime direction. For example, a person may make a short trip to the south to enter a freeway, which later turns north and passes near a given destination, or provides access to a direct arterial on which the destination may be located.

An advantage of a CPM that uses the production rule system is that, once experienced, a route can be retraced at will, regardless of where the traveller originates along the route. For example, assume a route is learned from A to B that involves eight segments. Assume further that another route from C to D is learned that crosses the AB route in the third segment. This should give the CD traveller the ability to remember and travel to either of the AB destinations once s/he is at the appropriate intersection. Only that sequence of production rules required to complete part of the AB trip need be activated.

This process of learning routes can fix network properties in memory. But nodes and segments may not necessarily be fixed in a spatial sense, unless segment distance, heading, and external frame of reference are all simultaneously stored. For example, one could remember segment sequence and segment length between multiple pairs of nodes, but quite inaccurately fix the end point locations. Such inaccuracies would inhibit shortcutting and spatial exploration between hitherto unconnected nodes, for the model would have no way of estimating whether or not the connected sequence that it had stored was the most effective way of joining the two places.

A recent attempt to build a cognitively aware disaggregate model of household travel behaviour has been undertaken by GÄRLING *et al.* (1991). This model has a series of modules: (a) the objective environment consisting of a transportation network and a set of functions that attract individuals, (b) a long-term calendar that contains the time available for the execution of each activity in a household's episodic activity cycle, (c) a constraints identifier that examines information from the objective environment and the activity pattern for assigned priorities and then lists possible obligatory and discretionary activities, (d) a sequencer which examines the list of possible activities and matches it with environmental constraints and priorities to determine the sequence of events that take place within a given time, and (e) a mental executor which chooses the transportation modes necessary for the execution of the different activities.

Wayfinding and Geographic Information Systems

Each activity defined for a traveller can be described by a set of productions. But these productions need to be implemented in a network context reflecting the idiosyncrasies of a real environment. This is where GISs become important in the modeling of wayfinding behavior. For example, in ARCINFO, the activation of NETWORK subroutines allows one to define different types of routes once a network is identified. In a U.S. city, for example, the appropriate city's TIGER files can provide the detailed street network required to activate production rules for different trip purposes.

In general, a network can be specified as a list of nodes and a list of links between pairs of nodes. Each node and arc (link) can be geo-referenced. In addition to the basic network, the GIS would contain landuse information for each block facing a road segment. Superimposed on this information could also be the socio-demographic information contained in the most disaggregate census units. For any trip purpose the subset of landuses at which that purpose can be satisfied can be identified. The problem then arises as to which combination of route segments should be used to fulfil a trip purpose. Accessing a 'Household Scheduler' (GÄRLING *et al.*, 1991) can determine if a single- or multiple-purpose and single- or multiple-stop trip is scheduled. This schedule is completed according to criteria specifying the time required to complete the purpose, the institutional constraints on opportune open times for access to the place at which a function could be accessed, preferences as to the temporal sequencing of scheduled activities, and selection of criteria (such as minimal time or distance covered) that allow a trip to be planned with the scheduling constraints in mind. Using a combination of a Scheduler and a GIS would further enable the network to be visually displayed on screen and the selected path or route to be highlighted. Accessing other network-based models (e.g. TRANSCAD or TRANPLAN) could then allow comparison between the chosen route and a route that would conform to traditional planning principles (e.g. shortest-path or travelling salesman principles).

Early work by GOLLEDGE and ZANNARAS (1973) suggested that route knowledge settles early into a fixed or habitual pattern, and the components of routes are oriented and integrated to conform to the traveller's guiding principles. According to PAILHOUS (1970), networks have at least two different levels, primary and secondary, and any particular journey is most likely to have at least three components: a secondary link to a primary entrance, a primary segment, and a link from the exiting node on this primary segment to a secondary connection that leads to a destination. I suspect there are more than two levels in a learned network structure, but this still remains to be proven. LEISER and ZILBERTSHATZ (1989) suggest that an interesting research direction is to explore what happens to route selection when networks develop special topological features such as congestion, bottlenecking, or gridlocking. This, of course, brings the academic wayfinding problem into touch with hard reality, and is undoubtedly a major direction for future research that seeks to combine wayfinding and a GIS.

Concluding Statement

Recognizing and locating places and finding routes between them are essential parts of the process of spatial knowledge acquisition. Often referred to as landmark and route knowledge or declarative and procedural knowledge, these represent the core of spatial knowledge—particularly what can be referred to as 'common sense spatial knowledge' which is the knowledge base for most people. Knowing places and routes suffices for everyday behavior. But when interpretation of an environment is needed, or when spatial inferences (such as taking shortcuts through unknown areas or deciding where an urban function might be found) is required, I suggest that another type of spatial knowledge—configurational or relational knowledge—is essential.

Configurational knowledge is that which underlies many geographical concepts—such as shape, pattern, distribution, and association. Examination of the processes needed to gain such knowledge has not been well researched. In contrast, a large literature exists on place recognition and wayfinding. As can be inferred from this paper, many active research programs exist in a variety of disciplines focused on landmarks and routes. Apart from the basic need to understand these concepts and their spatial outcomes (i.e. spatial behaviors), there is an emerging trend to apply spatial knowledge concepts in scenarios ranging from designing moon-walkers and automatically guided vehicles to understanding how disadvantaged children can best be helped to effectively learn and use their environments.

As we find out more about places, routes, and layouts, there will be a need to reexamine existing theories of environmental knowing, the spatial component of theories of development, and theories of the cognitive structuring of information. As we learn more about human understanding and use of space, it is apparent that spatial knowledge has a unique character that is not necessarily well described by existing theories or models of learning and understanding. It is important that geographers realize this and that they initiate work designed to explore more fully the concept base of the discipline they profess.

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