EFFECTIVE PROVISION OF NAVIGATION ASSISTANCE TO DRIVERS: A COGNITIVE SCIENCE APPROACH

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ABSTRACT

On-board computer-assisted navigation aid for drivers is an area of considerable research interest. Information on how humans learn spatial relations and how they communicate those relations to others should form the basis for such navigation aids. For example, both theoretical and empirical evidence from cognitive science suggests verbal (procedural) navigation advice may be more effective than a map (graphic output) displayed inside the vehicle. Probable reasons for this are discussed. Central issues related to navigation assistance for drivers are reviewed, and important directions for future research are suggested.

INTRODUCTION

Spatial navigation is one of the most basic abilities and essential survival skills of humans and most other animals. Human society often requires navigation in unfamiliar areas, and thus places strong emphasis on ability to give and receive directions for travel. Since spatial behaviour is such a central concern of geography, and spatial learning has been an area of geographic research, it is surprising that geographers and cartographers have devoted relatively little time to the study of the **communication** of spatial information which is embodied in formal and informal direction-giving, direction-receiving, and route-following.

In contrast, cognitive science has shown considerable concern with how people know and learn about geographic space; in fact, spatial learning is an important theme within cognitive science. Papers from the cognitive science literature by Kuipers (1978, 1983a, 1983b) on modelling spatial knowledge and learning, and by Riesbeck (1980) on judging the clarity of directions reveal important elements of the navigation process and supply a theoretical basis from which to proceed.

Recent activity in the study of human navigation has been sparked by technological innovation. Navigation aid systems for private automobiles are an area of commercial and academic interest, as indicated by a session at the recent Seventh International Symposium on Automated Cartography (Cooke, 1985; Streeter, 1985; White, 1985) and by various articles in the popular press. Such systems might be of particular interest in rental cars, and similar systems might prove valuable for taxicabs, delivery trucks, and emergency vehicles. On-board computer-assisted vehicle navigation aids for drivers are now available at moderate prices, and such technology will certainly become less expensive. Yet, several crucial questions remain about the content and form of the information they should provide.

We contend that information on how humans learn spatial relations, and how they communicate those relations to others, should form the basis for automated navigation aids for drivers. We therefore begin by reviewing in some detail a powerful model for cognitive representation of spatial knowledge, and by discussing some experiments which relate to the performance spatial navigation tasks. Then, we expose a number of issues relating to computer systems for the presentation of navigation information. Finally, we conclude by outlining what we feel are the major gaps in our knowledge of spatial learning and cartography, gaps which inhibit the design of systems and which provide many research opportunities for geographers and cartographers.

THEORETICAL BASIS: COGNITIVE SCIENCE AND SPATIAL KNOWLEDGE

Kuipers' Model of Spatial Learning

Benjamin Kuipers has developed a powerful computational theory for spatial knowledge. In particular, Kuipers' theory is concerned with the processes by which one learns about large-scale (geographic) space: "space whose structure cannot be perceived from a single vantage point, and which is learned by integrating local observations gathered over time" (Kuipers, 1983b, p. 1). This theory (implemented as a LISP program) was introduced as the TOUR model (Kuipers, 1978), and refined and expanded in a series of other papers. Kuipers' model accounts for a variety of states of partial knowledge in spatial learning, and Kuipers has claimed that "design alternatives **do not exist** at the level of the gross structure of the cognitive map" (Kuipers, 1983a, p. 358). Kuipers' model thus forms an appropriate theoretical basis for studies of the **communication** of spatial information for navigation and other purposes.

Kuipers' model organizes spatial information into three major categories:

> "**Sensorimotor Procedures:** Knowledge of a set of actions, and their sequence, required to travel from one place to another.
>
> **Topological Relations:** Knowledge of non-metrical properties of the external environment, such as containment, connectivity, and order.
>
> **Metrical Relations:** Knowledge of, and the ability to manipulate, magnitudes such as distance, direction, and relative position." (Kuipers, 1983b, p. 1).

For convenience, we will refer to these as **procedural, topological,** and **metrical** knowledge, respectively.

Procedural knowledge is based on two types of objects, **views** and **actions.** The term **view** is used to refer to the set of sensory inputs available at a particular place and orientation; the nature of a view allows one to determine whether or not two views are the same. An **action** is a motor operation that changes the current view (for example, a move or a turn). As one travels through large-scale space, one 'sees' a series of these views; some of these views are associated with actions such as turns from one street to the other. Procedural knowledge can be acquired by storing (i.e., learning) associative links of two types:

> "The link (V->A) has the meaning that when the view is V, the current action should be A.
>
> The link (V A)->V' has the meaning that if the action A is taken in the context of view V, the result will be view V'" (Kuipers, 1983b, p. 2).

A **route** consists simply of a series of (V->A) pairs. **Learning** such a route would consist of tranferring (V->A) pairs from short-term to long-term memory; such a route provides a **procedure** for getting from one place to another. It is possible to follow a route given only such an unordered collection of (V->A) pairs--following an action, the environment provides the next view, triggering the next action, et cetera. However, if links of the second type, namely (V A)->V', are stored as well, the person can 'replay' the trip in his/her mind, or explain it to someone else. As Kuipers (1983b, p. 1) has pointed out, storage of only (V->A) links would result in the not uncommon situation: "I can't tell you how to get there, but I can show you."

Kuipers proposes that many people assimilate information from procedural knowledge of routes and use this to build **topological knowledge** of large-scale space. At this level, a **place** is identified as the cycle of views after repeated turns at a point. Places may be common to more than one route. A **path** is a sequence of places, and often corresponds with a route. However, a path would not be a route if it has never been travelled in the real world, but only inferred from other experiences. Furthermore, places and paths are fixed features in the real world, whereas views and actions are sensorimotor experiences, and routes are procedures for navigation (Kuipers, 1983a, p. 356).

Paths are seen to **connect** places, and to **divide** space into **regions**. People with spatial knowledge at a topological level will usually know on which side of a major street (path) some known place lies, and will be able to plan new routes between places. However, the orientations of paths may be distorted, and places are not fitted into an over-all coordinate system. Sketch maps produced by people with this level of knowledge may have strong distortions, but often will be useful and fully functional for spatial navigation. Also, regions at one level of abstraction may be equivalent to places at another level.

Some individuals acquire spatial knowledge at the metrical level, wherein that knowledge is placed into the framework of a cartesian coordinate system. People with metrical spatial knowledge can point in the same direction that would be straight out their front door at home, and can provide estimated distances between places. Although not so stated by Kuipers, we feel that access to graphic, metrically-correct, maps almost certainly plays a key role in the learning of spatial information at this level.

<u>Kuipers' Model and Spatial Navigation</u>

We claim that it is useful to classify various forms of spatial information for navigation according to the three categories of spatial knowledge proposed by Kuipers. Verbal directions for getting from one place to another, presented in words either spoken or printed, represent information at a procedural level. Sketch maps with distortions (deliberate or other) represent a topological level of spatial information. Road maps and other planimetrically-correct maps represent a metrical level of information.

Clearly, procedural information (at least the next (V->A) pair) **must** be available in short-term memory in the brain of the traveller in order to allow the traveller to get from one place to another. If navigation information is provided at **any** level other than procedural (e.g., a map on paper or on a CRT), then one must do work to determine the relevant procedural instructions. This takes time and effort, may distract from other tasks, and may be subject to error.

Graphic Maps or Verbal Directions?

Interpreted this way, Kuipers' model accounts for the results of research by Streeter et al. (in press). Their study indicated that drivers may navigate more effectively when given verbal (vocal) directions, rather than a graphic map. Streeter and her co-workers compared four methods for receiving navigation during automobile driving. These methods are: (1) Standard road maps; (2) customized road maps (north at top); (3) verbal instructions from tape recorder; and (4) a combination of methods (2) and (3).

Performance of test subjects was evaluated in terms of travel time, number of errors, and other measures. They found, not surprisingly, that method (1) (the 'control' condition) produced the poorest performance. However, the best performance was observed when the subjects had only the tape recorder to guide them. (This method involved a customized tape recorder with two buttons: one to repeat the last instruction, and the other to play the next one.) Significantly, the 'customized map' group (method 2) had the second-worst performance level. It also seems that providing the subjects with maps in addition to the tape recorders (method 4) detracted from performance given the tape recorder only. Perhaps the map constituted a distraction, reducing the ability of the subject to concentrate on the tape; alternatively, by providing a means to recover from errors, it may have reduced the perceived **need** to concentrate on the tape.

The main result of Streeter's experiment appears to confirm the implication we have drawn form Kuipers' model, namely that provision of navigation information at the procedural level should be easier to assimilate than would be graphic topological or metrical information.

NAVIGATION AIDS FOR DRIVERS: KEY ISSUES

In this section, we present a number of issues related to the provision of navigation aids to drivers. Many of these issues lead to two or more alternatives. An ideal system might provide all of these alternatives, as user-specific options selected either explictly or through a series of computer-administered questions or tests. However, provision of such a wide range of options would probably make a system unduly cumbersome. Furthermore, users may not fully understand the differences among choices presented, and may be intimidated by a system which presents too many 'complicated' choices.

Form of presentation

Perhaps the most fundamental issue in computerized navigation aids for drivers involves the mode of presentation: should the information be presented in graphic form (as a map), or in verbal form (as procedural directions)? Both theory (Kuipers) and empirical evidence (Streeter et al.) suggest that verbal directions may be more effective than maps, but anecdotal evidence suggests that some users would not want to 'trust' a computer to give them directions. (They would, however, trust a map drawn by the same computer!) Furthermore, a system to provide verbal directions **must** include an algorithm for route selection, raising several new issues.

Finally, in a post-travel survey of 27 people provided with both verbal directions and a map to a novel destination, 7 preferred the verbal directions, 10 preferred the map provided, 2 rated them as equal, and 8 did not use either (Mark and McGranaghan, in prep.). This small sample suggests that there is no strong consensus of preference on this issue. Streeter and Vitello (in press) found that "self-described good navigators like and use maps... whereas poor naviagtors tend not to use maps [and] prefer verbal directions" (Streeter and Vitello, in press, ms. p. 1).

Graphic Design

If the data are to be presented graphically, then one is faced with all the usual issues of map design, under the constraints of the display technology and intended use. One point of interest is the orientation of the map. Should the map be presented with north at the top (north-up mode), or with the direction of travel at the top (heading-up mode)? Informal surveys suggest that people may prefer a north-up presentation most of the time, but a heading-up presentation for complicated situations.

The use of CRTs for on-board map presentation raises the issue of optimal colour and illuminance contrast among map symbols. Recent research on choropleth map perception (McGranaghan, 1985b) suggests that such maps should be presented on a light background. Does this effect apply to line symbols employed in road maps? The issue must be addressed within the context of changing ambient illumination in the driver's compartment.

Route Selection

As noted above, the computer must perform route selection in order to provide verbal directions between arbitrary origins and destinations. Route selection advice could also be a useful component of a graphic presentation of navigation information. Finding 'any' route to a goal (destination) would seldom be adequate, and so the route search procedure must either find an optimal (shortest) route, or at least find an adequate heuristic approximation to the optimal. Choice of an appropriate state-space search algorithm is one issue in such a system.

Another issue is the cost function which the search algorithm attempts to minimize. Naively, one might simply find the shortest path, minimizing the total metric length of the path. However, shortest paths often are difficult to navigate along. Elliott and Lesk (1982) have suggested algorithms which attempt to find minimum effort paths; to accomplish this, they include in the cost function heuristic differential costs of, for example, left- and right-turns. Alternatively, Mark (1985) proposed that 'ease of description' is a useful heuristic component of route cost. His approach minimizes the weighted sum of the metric path length and the length (number of elements) of the verbal description of the path.

Positioning issues

Whereas paper road maps do not provide drivers with absolute position information (a 'you-are-here' symbol), it seems obvious that this would be useful in a computer mapping system. A 'you-are-here' symbol could move about on the computer map, or could remain at the center of the map frame, with the map window moving accordingly. Such a system could determine absolute positions through the use of Loran or of a navigation satellite (signal-dependent positioning); current civilian Loran and satellite technology, however, do not provide sufficient accuracy at present for such an application. Alternatively, the navigation system could be based on 'dead reckoning', sensing headings and distance travelled (autonomous positioning); given an initial location and heading, the computer could keep track of the current position, correcting it through the relation of turning points to road intersections in the data base. Of course, position at the start of the trip is essential for verbal (procedural) route description. If the system kept track of position during the trip, it could detect errors and provide directions to correct them.

Data issues

The total quantity of data needed to support a navigation-aid system is very large; for example, the road network of the San Francisco Bay area requires between 7 and 10 megabytes of data storage space (Zavoli et al., 1985). Both data-structuring and data location are significant issues. It may in fact be possible to incorporate spatial concepts, based on cognitive models, into the design of data-structures themselves (McGranaghan, 1985a).

Two distinct data location strategies are available: in one, all data are kept in the vehicle (on-board data-base); in the other, data are transmitted to the vehicle as needed (broadcast data-base). The on-board strategy has the advantage of independence. Furthermore, it avoids an additional data link in the system, another place for error.

On-board data storage raises the issues of the storage medium and the data structure. White (personal communication to M. Gould, 1986) states that cassette tapes represent the only currently-available storage medium which meets the requirements of on-board systems. However, this may soon change, as Schipper (1984) describes a system based on Compact Disc (CD-ROM) technology. The CD-ROM would seem to have many advantages. For one, optical disks support random-access data retrieval, whereas a cassette tape provides only sequential access. Secondly, a cassette can store about 3.5 megabytes of information, and thus 3 cassettes are needed to store the aforementioned San Francisco Bay area data set (Zavoli et al., 1985); in contrast, the data capacity of a CD-ROM is about 500 megabytes (Chen, 1986). In addition, CDs are not subject to damage by water or magnetic fields, have no moving parts, and do not wear out with repeated access (Chen, 1986).

Although on-board data systems might be more stable than broadcast systems, the latter do offer one notable advantage: such systems can be constantly updated, and can provide data on ephemeral features such as construction hazards or even accident locations and traffic jams. Of course, a hybrid system could use on-board data for a base map and broadcast data for time-dependent information.

Use of Maps During Trip Planning, Rather Than During Travel

Mark and McGranaghan (in prep.) found that, of 29 subjects travelling to a novel destination near an area familiar to them, 18 consulted navigation aids during trip planning, whereas only 9 used them during the trip itself. This effect may be even more pronounced for unfamiliar areas. When people travel to a new or unfamiliar city and then drive around (in either their own car or in a rented car), the need for some form of navigation aid becomes much greater. Mark and McGranaghan (in prep.) found that 42 of 48 subjects (87%) "always" attempt to obtain a map of a new city when travelling, and that 31 subjects (65%) try to obtain such a map **before** they travel. Evidently, travellers represent important consumers of navigation information.

Specific Needs of Different User-groups

Yet another set of issues relates to the different needs of different types of users. For private cars, system use might be similar to map use. Many drivers use road maps in their home areas, largely when outside their neighbourhoods. A survey of 54 drivers found that 33 of them (61%) keep one or more local road maps in their cars (Mark and McGranaghan, in prep.). However, consultation of either maps or a digital system might be expected to be infrequent for drivers in their home areas.

Emergency vehicles, delivery vehicles, and taxicabs represent another class of potential users. Whereas drivers of these vehicles typically would learn their areas quickly, and thus have little need for autonomous on-board systems, broadcast traffic- and road-condition data could be very useful for these users. Also, algorithms to determine destination sequences and perhaps route details would be helpful for variable, multi-destination delivery situations.

RESEARCH NEEDS AND FUTURE DIRECTIONS

Kuipers' model of spatial learning, and its apparent confirmation in Streeter and others' study of 57 subjects, suggests that the use of a graphic (map) presentation in existing driver navigation aid systems may be premature. However, more research will be needed before one can recommend to industry the adoption of a verbal-procedural basis for such systems. Furthermore, the relative importance of the 'verbal-vs.-spatial' and 'aural-vs.-visual' differences between Streeter and others' maps and tape recorded instructions must be explored. It is quite possible that both differences are important. When the navigation aid is a graphic map, the actions to be taken (procedures) must be derived (extracted) from the map by the user, even if the route to be taken is shown distinctly; thus, procedural directions may be easier to follow simply because the driver is not required to do as much work. Secondly, the use of the aural sensory input channel may be less distracting from the predominantly visual tasks involved in actually driving the car. Thus, experiments which compare aural verbal instructions with verbal directions given on a printed script or a CRT or LED screen should also be performed.

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