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Cognitive Maps, Spatial Abilities, and Human Wayfinding

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Abstract: In this paper we discuss the relations between cognitive maps, spatial abilities and human wayfinding, particularly in the context of traveling without the use of sight. Initially we discuss the nature of cognitive maps and the process of cognitive mapping as mechanisms for developing person to object (egocentric) and object to object (allocentric) internal representations. Imperfections in encoding either relations can introduce imperfections in representations of environments in memory. This, together with individual differences in human spatial abilities, can result in data manipulations that produce error. When information stored in long term memory is brought into working memory for purposes of decision making and choice behavior (as in route selection), the result may be the selection of an inefficient or incorrect path. We explore the connection between environmental learning and cognitive maps in the context of learning a route in two different cultural environments-Belfast (Northern Ireland) and Santa Barbara (California). Blind, vision impaired, and sighted volunteers traveled and learned routes of approximately the same length (1.2 miles) in their respective urban environments. An initial trial was experimenter guided; three following trials were regarded as "test" trials where the participants learned the route and performed route fixing tasks including pointing between designated places, verbally describing the route after each completion, and building a model of the route using metallic strips on a magnetic board. Results indicated that by the end of the third test trial, and using the reinforcing strategies, the results of the blind or vision impaired participants could not be statistically differentiated from those of the sighted participants. This indicated that the wayfinding abilities of the three groups were equivalent in this experiment and suggested that spatial abilities were potentially the same in each group but that lack of sight interfered with putting knowledge into action.

Key words: cognitive map, individual differences, wayfinding, blind and vision impaired, participant's route learning

Definitions

Cognitive map

Cognitive maps are the internal representation of experienced external environments, including the spatial relations among features and objects. There is as yet no clear evidence that they take a cartographic form. Rather, it appears that objects in an environment are coded in specific place cells and that these place cells may be randomly distributed throughout the brain. Place-based coding allows one to determine where one is at any moment and what place related objects should occur in surrounding space. As such, this internal representation provides the basic knowledge of how to get from one place to another, or how to communicate spatial knowledge to others. Cognitive mapping is the process of encoding, storing, and manipulating experienced and sensed geo-referenced information. What guides this processing remains unknown and is being actively researched in neuropsychology and related fields.

Sholl (1996) suggests that travel requires humans to activate two processes that facilitate spatial knowledge acquisition—*person-to-object* relations that dynamically alter as movement takes place (which is also called egocentric referencing), and *object-to-object* relations which remain stable while a person undertakes movement (sometimes called the *anchoring structure of a cognitive map*). Poor person-to-object comprehension can explain why a traveler can become locally disoriented even though still comprehending the basic structure of the larger environment through which movement is taking place. Incorrectly encoding local and more general object-to-object relations results in misspecifying the anchor point geometry on which cognitive maps are based and can produce the distortions and fragmentation often found in spatial products.

Cognitive maps as wayfinding tools

A variety of guidance instruments and materials are available for human wayfinding. Nevertheless, humans tend to use cognitively stored and recalled information more than these supplementary aids. This is because most trips are made in familiar or partly familiar environments when experience plays a more significant role than does reference to supplemental data such as maps.

There are three different types of knowledge frequently specified with relation to human wayfinding: 1. Route learning (or systematic encoding of the route geometry by itself); 2. Route based knowledge acquisition or understanding of the place of the route in a larger frame of reference; and 3. Survey or configural knowledge which allows a route to be selected from a more general pervasive environmental knowledge structure in which different route segments can be linked into a network that can provide a significant frame of reference for local or global environmental knowledge.

Most people, when building a knowledge structure or representation of places and environments, do not use instruments or mapped representations but rely on the basic senses of vision, acoustics, touch, and sensory motor or proprioceptive experience to identify, encode, and store environmental knowledge. Thus, general environmental knowledge is largely obtained during processes of moving through an environment (MacEachren 1992). But human based methods carry all the error baggage that instruments were designed to eliminate. So it can be expected that spatial representations in humans are incomplete and error prone, producing the distortion or fragmentation of spatial products that have been found by numerous researchers.

Spatial abilities

The degrees of knowledge about places, locations, or landmarks or other components of a route vary among people (i.e., there are individual differences in the nature and extent of environmental knowledge). There is also abundant evidence that there are developmental changes in the ability of humans to learn both route and survey information (Piaget and Inhelder 1967). However, several recent research publications have criticized the strict Piaget type developmental theory of spatial knowledge acquisition as interpreted by Siegel and White (1975) (e.g. Liben 1981; Montello 1998). Certainly, there are well-established differences between preschool, preteen, teenage, and adult abilities to learn environments and navigate through them. For example, Pellegrino, Golledge, Gale, and Ruggles (1987) report on a series of tasks involving route sequencing by pre-teen, teenage, and adult participants and illustrated significantly large differences between all group pairs.

There also is some evidence that males and females acquire different types of knowledge to help them in their wayfinding tasks (e.g., women use more landmarks, men use more orientation and geometric or frame-related processes—see Self and Golledge 2000). Further, humans do not all behave the same way in the same environments, partly because of different levels of familiarity, partly because of different trip purposes that require them to give different saliences to objects, and partly because of differing spatial abilities. For example, adults and children do not usually have the same understanding of spatial layout or the configurational structure of specific environments (see Bell 2000).

Spatial abilities are often grouped according to their function—i.e. according to the tasks or situations in which they come into play or according to the purpose they may serve. Allen (1999) suggests that the most widely recognized spatial abilities from the psychometric literature are visualization, speeded rotation, and spatial orientation. Visualization concerns the ability to imagine or anticipate the appearance of complex figures or objects after a prescribed transformation (e.g. paper folding). Speeded rotation (sometimes called spatial relations) involves the ability to determine whether one stimulus is a rotated version of another. Orientation is the ability of an observer to anticipate the appearance of an object from a proscribed perspective.

Spatial abilities fall into one of three families concerning: a) a stationary individual and manipulable objects; b) a stationary or mobile individual and moving objects; and c) a mobile individual and stationary objects. Wayfinding specifically is related to the latter of these groupings. Spatial abilities, therefore, are a very important component of making and using cognitive maps, as well as playing a critical role in human wayfinding.

Human wayfinding

There are two ways to describe the processes behind human movement. One is called *navigation* (the processing of spatial information regarding position and rate of travel between identifiable origins and destinations summarized as a course to be followed). The second is *wayfinding*, which involves selecting path segments from an existing network and linking them as one travels along a specific path. Usually the path selected varies with trip purpose; as these vary, so do needs to select travel speed, efficiency, and outlay of effort. The process of wayfinding requires an ability to know origins and seek a destination that may have never before been visited and about which little may be known, to determine turn angles in appropriate sequence, to recall segment lengths and numbers, to specify the direction of movement along a segment or between turn angles, to differentiate between on-route and off-route cues that prime knowledge of current position, to maintain orientation, to estimate location based on information about distant landmarks, and to embed a course within a particular reference frame which may be absolute or relational. Wayfinding is a purposive, directed, and motivated activity. It may be observed and recorded as a *trace* of sensory motor actions through an environment. The trace is called the *route*. The route results from implementing a *travel plan*, which is an a priori decision making activity that defines the sequence of segments and turn angles that comprise the route to be followed. The travel plan is the outcome of using a particular strategy for *path selection*. The *criteria* used in path selection include shortest distance, shortest time, minimizing turns, longest leg first, and so on (see Table 1). The *legibility* of a route is the ease with which it can become known, or (in the environmental sense) the ease with which relevant cues or features needed to guide move-

Table 1. Types of route selection criteria

Longest leg first
Shortest leg first
Fewest turns
Fewest lights or stop signs
Fewest obstacles or obstructions
Variety seeking behavior
Minimizing negative externalities (e.g. pollution)
Avoiding congestion
Avoiding detours
Responding to actual or perceived congestion
Minimizing the number of segments in a chosen route
Minimizing the number of left turns
Minimizing the number of nonorthogonal intersections
Minimizing the number of curved segments
Ensuring locomotion remains within a given width (corridor) surrounding a straight line connection between origin and destination
Maximizing aesthetics
Minimizing effort
Minimizing actual or perceived cost
Minimizing the number of inter-modal transfers
Minimizing the number of layers of a road, street, or highway system that have to be utilized
Fastest route
Least hazardous in terms of known accidents
Least likely to be patrolled by authorities
Minimizing exposure to truck or other heavy freight traffic

ment decisions can be organized into a coherent pattern. Legibility influences the rate at which an environment can be learned. Wayfinding uses a variety of strategies such as: (i) piloting (navigation from landmark to landmark), (ii) spatial search and exploration, (iii) distant landmark recognition, and (iv) use of celestial compasses. Returning home (Homing) uses strategies such as (i) piloting, (ii) route reversal, (iii) shortcutting, (iv) dead reckoning or path integration, and (v) constrained search and exploration.

Repeated route following facilitates remembering path components and recalling them for later use. This is called *route learning*. Paths or routes are represented as *one-dimensional linked segments* or, after integration with other paths, as *networked configurations*. The latter, along with on-and off-route landmarks, the spatial relations among them, and other spatial and non-spatial features of places (such as prominence of visible form), make up the anchoring layout of a remembered environment (e.g. the anchoring of a cognitive map). Route learning and route following strategies help build up cognitive maps via an integration process. Difficulties experienced in mentally integrating different routes and their associated features into network structures help to explain why cognitive maps may be fragmented, distorted, and irregular.

Human wayfinding is very trip-purpose dependent and it is difficult to attribute any specific cognitive process to wayfinding generally. The question remains as to whether specific purposes are better served by certain types of wayfinding strategies. For example, journey to work, journey to school, and journey for convenience shopping are often habitual activities that require minimized en-route decision making; journey for recreation or leisure may be undertaken as a search and exploration process and requires constant locational updating and destination fixing. As the purpose behind activities changes, the path selection criteria can change, and, as a result, the route that is followed may also change.

Strategies for Assisting Route Learning and Wayfinding

Introduction

Evidence of route learning is specified by the ability to (i) undertake route reversals, (ii) perform same direction route retraces on successive trials, (iii) recognize local cues when given photographic slides of on-route objects, (iv) verbally describe a route to be followed by another individual in a way comprehensible to the other person, (v) create a spatial product (such as a sketch map or three-dimensional model) based on recalled knowledge, and (vi) indicate direction by angle estimation or pointing from real or imagined on-route locations. A significant research question asks which of these procedures are most likely to be activated in any given environment and which produce the greatest reinforcing effect of the route learning procedure. In general, these procedures can be divided into (a) those requiring memorization and recall of the route chosen and (b) those that require spatial updating to estimate the distance and direction required to return directly home using shortcut methods.

Procedures for Belfast and Santa Barbara experiments

We undertook a series of experiments in Belfast (Northern Ireland) and Santa Barbara (California). In each environment we used 10 sighted, 10 visually impaired, and 10 blind individuals as participants. The two place-based sets of participants were matched closely for age, socio-economic status, and educational background. Each participant first was required to take the experimenter over a route that was personally familiar to them, thus allowing the experimenter to observe the types of behavior they exhibited. This established a performance base and provided a training exercise prior to each participant undertaking the set of experimental tasks to be performed in the unfamiliar test environment. Table 2 shows the aggregate results from participants' travel activities in their familiar environments. They were then required to learn a new route in a

Table 2. Familiar route* (benchmark) results

	Number of participants	(a) Model bidimensional regression coefficient	(b) Pointing absolute error	(c) Distance regression	(d) Route length (m)	(e) Number of turns	(f) Number of intersections
Belfast							
Vision impaired	12*	0.83	17.1	0.69	1233	5.2	2.2
Blind	11*	0.89	17.7	0.80	1063	4.2	1.9
Santa Barbara							
Vision impaired	10	0.74	21.3	0.74	1013	3.5	2.9
Blind	10	0.82	22.3	0.79	1303	3.3	3.8

Note: All values indicated are the mean for the group.

(a) This coefficient varies between 0 (no association) and 1 (perfect association).

(b) Figures are average degrees of error (absolute values).

(c) Regression between distance between landmarks in the environment and participants ratio scaled estimates.

(d) Actual length of familiar route in the environment.

(e) Number of turns on the familiar route in the environment.

(f) Number of intersections on the familiar route in the environment.

Data in d, e, and f above are included as benchmark indicators of the complexity of the familiar routes the participants regularly travel in the environment.

* Higher numbers in column 1 include one or two participants who completed the 'familiar route' stage and whose data appears in this table, but for reasons outside their control were unable to complete the main study; they were not considered as part of the main study ($n=10$ for all groups).

completely unfamiliar environment in Belfast or Santa Barbara respectively. To do this the participants were given 4 trials-the first was an experimenter-guided trial and the next 3 were learning and evaluation trials.

The same procedure was used in each test environment. Each experiment took place over a mile long route with 16 to 20 turns. Figure 1 illustrates the Belfast and Santa Barbara routes. On the guided trial, participants were informed that the route had been divided into four segments and that they would be guided between the start and end of each segment. The segment ends would be identified by a named landmark. They were asked to remember the names and locations of these landmarks. The researchers did not physically lead respondents over any part of the route; they merely walked with them. Directional guidance was given in an indirect way, such as "You need to turn to face my voice," or "You need to cross the road you have just been walking down." In this way, respondents had to code directions through their own actions. Participants were informed when they had reached a segment end and were then given the landmark name. Upon completion of the first route, they were driven back to the start via a different circuitous route. Sighted respondents were blindfolded for this return trip.

Learning tasks

On the three consecutive trials, participants were requested to perform a number of tasks. The first was a pointing task to and from the three landmarks that anchored each segment as well as to and from the start and end points of the route. During the second task, participants were asked to verbally describe how they traveled along the route. The third task required estimating distances between start and end points and intervening landmarks, using a ratio scaling technique. The final task involved constructing a model of the route using black magnetic pieces against a white metallic board. At the end of all four trials they also completed a supplementary task (estimating which distances are further between paired locations) and participated in a debriefing interview.

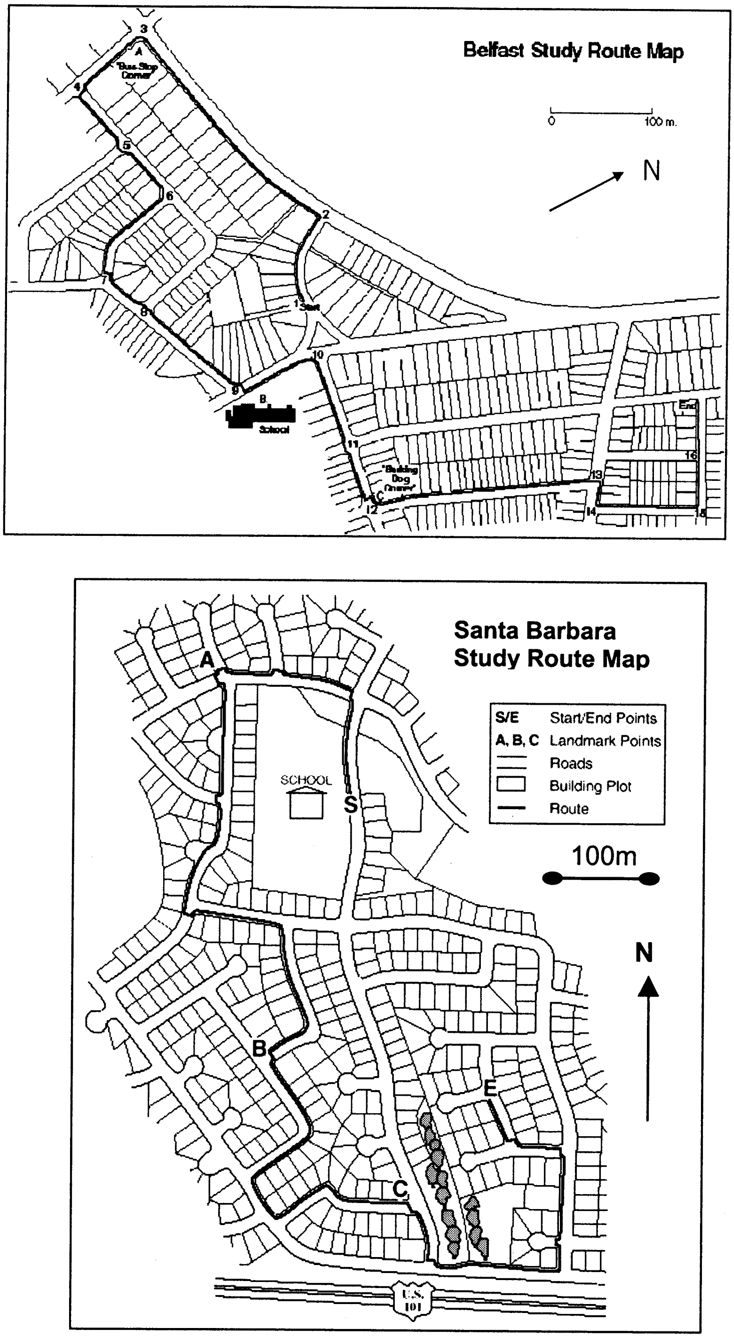


Figure 1. Belfast and Santa Barbara study routes.

Results

Figures 2a, b, c and 3a, b, c summarize the degree-of-route learning by trial in the two study areas. In each Diagram it is obvious that the sighted participants learn more quickly, but, by the end of the 3rd learning trial, convergence towards error-free performance occurs. Figures 2a and 3a summarize the results of the route-learning task, while Figures 2b and 3b and 2c and 3c show comparative results using off-route strategies.

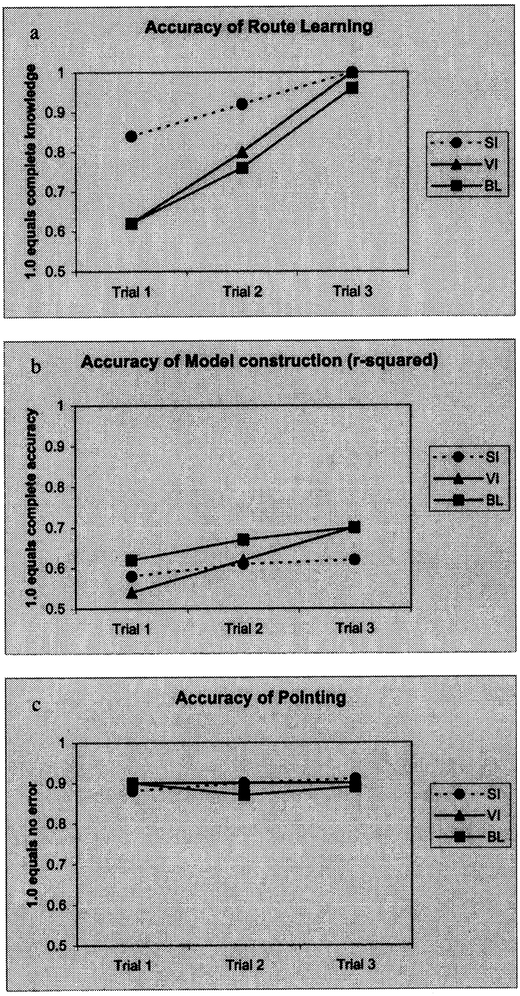


Figure 2. Belfast learning curves.

Note: SI=Sighted group; VI=Vision Impaired group; BL=Blind group

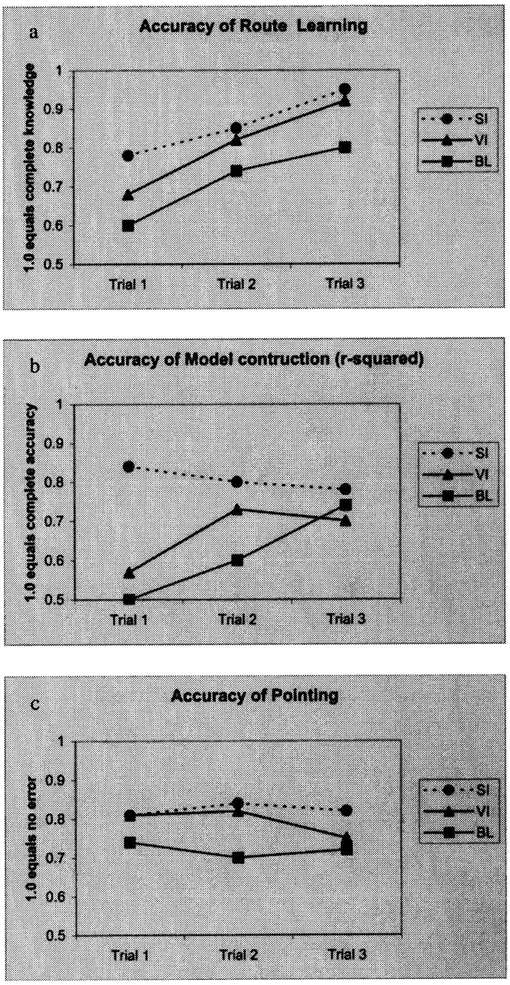
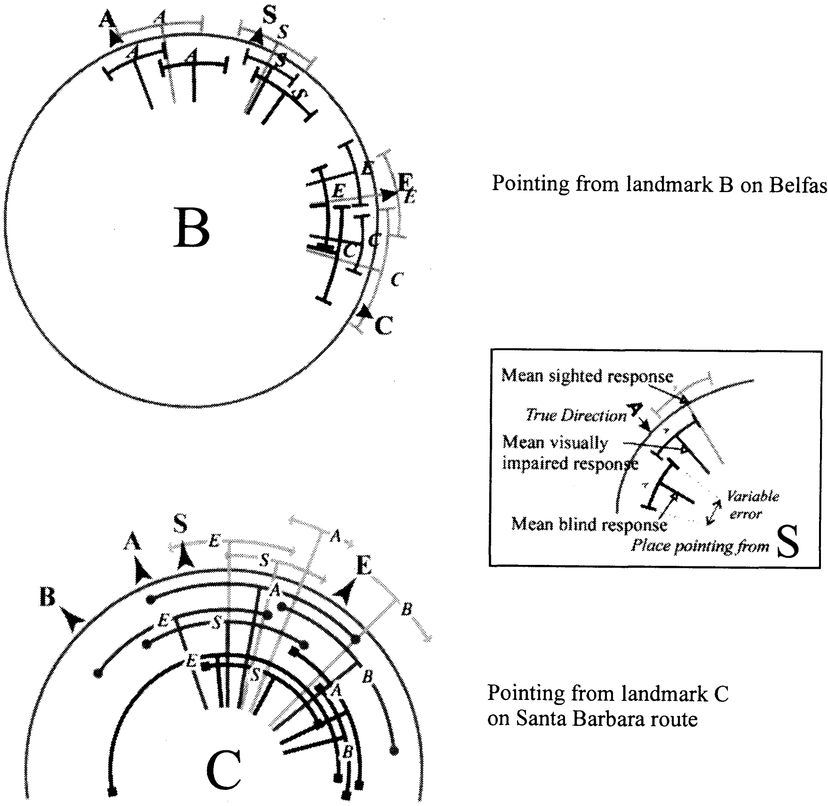


Figure 3. Santa Barbara learning curves.

Note: SI=Sighted group; VI=Vision Impaired group; BL=Blind group

Figure 4 displays an extract of the pointing results, illustrating constant and variable error for landmark 2 (B) in Belfast and Santa Barbara. The mean direction for each group, across all trials, pointing to a specific place is shown by a line radiating from the place of pointing. The specific place they are pointing to is labeled at the end of this line. The circular standard deviation for that mean is represented graphically by an arc on the end of the mean observation line. The greater the size of the arc, the greater the variable error. Constant error is shown by the difference between the mean line and the true direction. On the diagram, the results for the blind group are shown by the set of heavier black lines closest to the diagram's center; sighted results are shown by the set of faint lines further from the center; vision impaired results are shown by lighter solid lines halfway between the blind and sighted group representations.

In Belfast, pointing was accurate for all groups. The mean line was close to correct direction and there was minimal variance. In Santa Barbara, overall pointing performance was poor across all groups. It is suggested that the additional junctions and curves that were part of the overall configural knowledge made learning more difficult. There were 360 degrees more body rotation on the Santa Barbara route



Pointing from landmark B on Belfast route

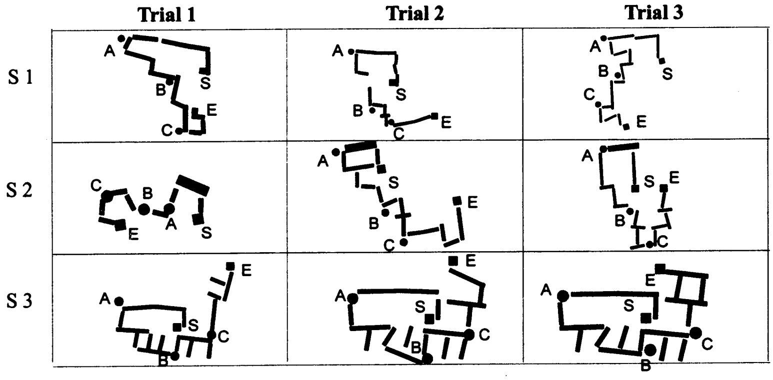
Pointing from landmark C on Santa Barbara route

Figure 4. Pointing performance for landmark 2 in Belfast and Santa Barbara.

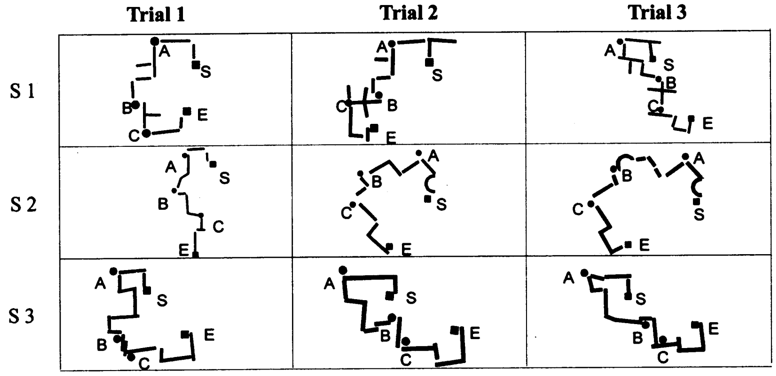
compared to Belfast. These body rotations took place along irregular curves rather than the more common 90 degree turns in Belfast. The large variation across all group pointings in Santa Barbara, and the particularly large variable errors among the vision impaired and blind groups, highlights the disorientating nature of some of the route segments.

A series of paired two-sample *t*-tests of the absolute and relative error scores for individuals, averaged across groups for the whole route, showed no significant difference between the groups (sighted, visually impaired, and blind), and no learning effect across the trials. When the Belfast data was analyzed at a disaggregate level with ANOVA, there were similarly no significant effects for the group ($F(2,27)=1.061$, $p<0.36$), although the early blind performed marginally worse than the sighted and visually impaired groups (blind mean=22.8°, sighted mean 18.5°, visually impaired mean 18.7°). An absolute error of 90° represents a chance response. Performance errors are generally low and it is particularly salient that there is no significant difference between the group with sight and the groups with impaired or no sight. There was a significant effect for trial $F(2,54)=8.467$ $p<0.001$. However, the participants' pointing was less accurate on the Santa Barbara route, with mean absolute error scores for each group being substantially higher (blind mean=50.0°, sighted mean 29.6°, visually impaired mean 34.7°). The difference between the groups was significant ($F(2,27)$ 9.802, $p<0.05$). From participant observation and verbal feedback during the debriefing interview, it became apparent that the Santa Barbara route was less environmentally legible to all groups when compared to the Belfast route. This problem of legibility was worse for the groups without vision. The Santa Barbara route involved the negotiation of several curves within street segments that ranged from shallow to ninety-degree bends. For all participants, these curves made it harder to establish a coherent survey

Blind participants reconstruction of the route (Belfast)



Visually impaired participants reconstruction of the route (Belfast)



Sighted participants reconstruction of the route (Belfast)

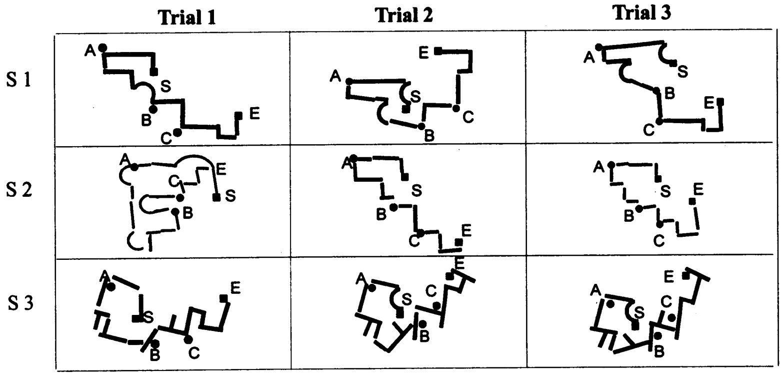
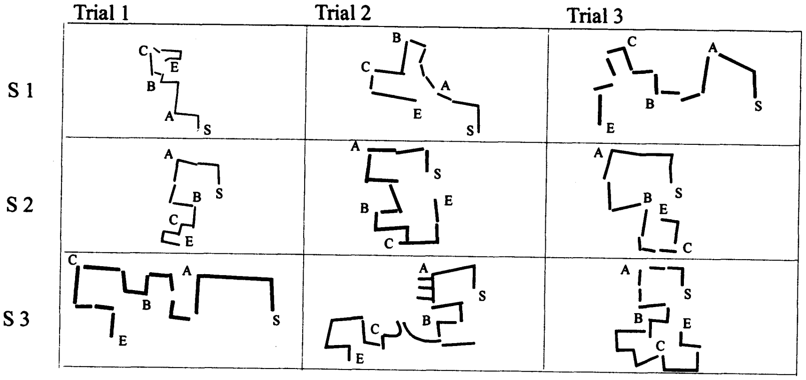


Figure 5. Examples of model construction of route: Belfast participants.

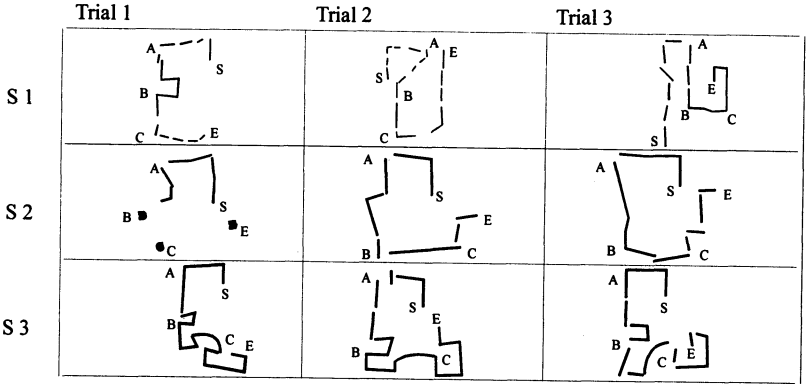
frame of reference. Figure 6 displays the higher variable error (length of arc) and widespread poor constant error for all groups in Santa Barbara when compared to Belfast groups.

Figures 5 and 6 show examples of the post-hoc table model building experiments. For the purpose of this study, the topology of the route refers to the correct sequencing of nodes and route segments (junctions right, left, and straight-on along the length of the route). These measures were derived from the table models. A 'topologically correct' route would be a route whose sequence of nodes and route segments matches that of the actual route. This

Santa Barbara: Study route models - blind participants



Santa Barbara: Study route models - visually impaired participants



Santa Barbara: Study route models - sighted participants

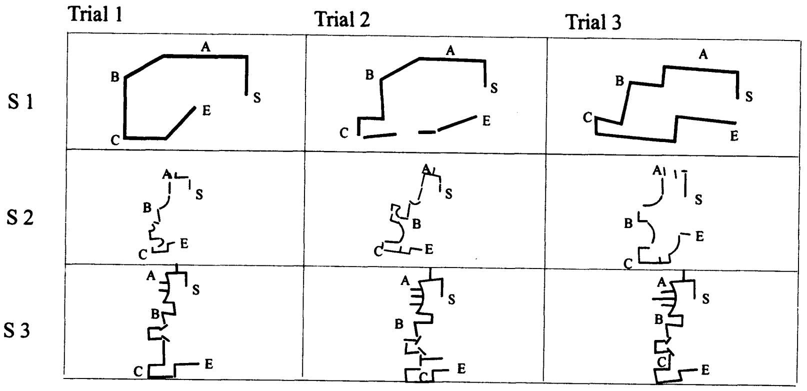


Figure 6. Examples of model construction of route: Santa Barbara participants.

measure can be operationalized by calculating the sequence of rights, lefts, and straight-ons from the start to the end of the route. Clearly, when assessing topological correctness of the models, account has to be made of omissions and errors. Otherwise an omission in the model will lead to cumulative "out-of sequence" errors. Consequently, the remaining junctions may be represented correctly, but are miscoded as the sequence of junctions is misplaced by the omission. To avoid this problem, the sequence of route segments was anchored about the landmarks. That is, a right or left turn was allocated to a preceding or following landmark when an error or omission occurred. This allocation was crosschecked against the video model talk-aloud protocol to confirm the participants intended junction placement. Each junction (16 choice points) was then coded as: (1) correct; (2) incorrect; or (3) missing.

The effect of the trials upon topological structure was highly significant ($F(2,54)=11.859$, $p<0.0001$) (the mean error score across groups decreased from 1.6958 for trial 1 to 1.4521 for trial 3). Individual junctions were represented very differently and had a disproportionate effect upon topological scores ($F(15,405)=40.563$, $p<0.0001$). The effect of level of sight was found to be insignificant ($F(2,27)=0.338$, $p=0.717$). In other words, there were no significant differences in the topological structure of the routes for members of blind, visually impaired, and sighted groups. Similarly, there were no differences across trials and between groups ($F(4,54)=0.734$, $p<0.5$), suggesting that each group learned at a similar rate.

Discussion

Analysis revealed that, while there were differences in the ability to retrace the route (with visually impaired and blind people deviating from the route or committing more errors more frequently in the early trials than sighted people), there were no statistically significant differences between the sighted, visually impaired, and blind groups in their ability to (i) learn the route after 3 trials, (ii) construct a model of the route, and (iii) point to locations along a route.

The evidence suggests that the visually impaired and blind participants deviated from the route not because of a lack of spatial understanding but because of a lack of visual perception that restricted their ability to recognize location cues along the route as they traversed it. Our data reveal that people with severe visual impairments are capable of learning a complex route through an urban environment both quickly and efficiently, and that their levels of spatial knowledge and their abilities to process such knowledge becomes equivalent to those of sighted individuals within a short time-frame. Whereas a sighted person had generally learned to retrace the route without mistakes by the second trial, the visually impaired and blind participants could do so by the fourth trial (one learning and three test trials). The navigation problem facing visually impaired and blind participants appeared, therefore, to lie in learning new environments independently and in articulating their knowledge in wayfinding practices. The process of "active" learning, where routes are learnt through independent travel reinforced through distance evaluation, directional pointing, and the recreation of an environment via model-making or verbal description, may be of critical importance to increasing spatial independence.

The results reveal that naturalistic tests measure related but different facets of knowledge and ability. The route retrace task measures the ability of an individual to use acquired spatial knowledge. Model and pointing tasks measure the levels of accumulated spatial knowledge. The tests indicate that people with severe visual impairments do possess the same abilities to process and construct spatial knowledge, but their lack of vision interferes with putting knowledge into actions effectively and as quickly as sighted people.

It should be noted that, during de-briefing sessions and follow up interviews, many of the blind and visually impaired participants expressed a strong preference for the way in which they learnt the route. They suggested that the tasks of pointing and model building forced them to explore and reconstruct their spatial knowledge, to "actively learn and think about the route, and how it all went together" (totally blind participant). The methodology of the study may then have 'elevated' the spatial cognition of the individuals with partial or no sight. This illustrates that, for vision impaired people with suitable training, structured presentations of and access to the geographic environment in route learning can become comparable to those of the sighted.

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