The Heuristics of Spatial Cognition

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Abstract

Distance estimation has been used extensively in the investigation of cognitive maps, yet it is not well understood as a cognitive process in its own right and, as a result, has been viewed as a simple read-out from a spatial representation. In contrast, this paper considers distance estimation to be a complex mental process in which heuristics guide the choice of strategies. Specifically, verbal protocols were collected on a distance estimation task for 20 undergraduates using a variety of city pairs in U.S. and Canada. On the basis of these data, distance estimation is shown to be a constructive process, using a relatively limited number of heuristics, such as addition, hedges and ratios. The choice of heuristics and the time to make a judgment are shown to be related to variables such as the familiarity of locations and the distance to be judged. The advantage of viewing distance estimation as a constructive process rather than a passive readout off an internal map is argued.

Introduction

Spatial reasoning and spatial cognition provides an important domain for the study of reasoning processes (e.g., Furnas 1990, Byrne & Johnson-Laird 1989), narrative comprehension (e.g., Bower & Morrow 1990), expertise (e.g., Chase & Chi 1981), artificial intelligence (e.g., Kuipers 1978; Kuipers & Levitt 1988) and the representation of knowledge (e.g., McNamara, Hardy, & Hirtle 1989). Within this domain, the methodological advances during the past decade have been notable. There has been a positive shift from hand-drawn sketch map methodologies to the use of indirect measurements (Evans 1980; Siegel 1981). However, just as early work on spatial memory assumed that sketch maps directly tapped one's internal representation (e.g., Lynch 1960), the later work makes equally restrictive assumptions of cognitive processes. Specifically, there has been a recent reliance on the use of distance estimation as a primary measure, examined either alone (e.g., Allen 1981), in conjunction with MDS (e.g., Baird 1979; Magaña, Evans, & Romney 1981), or through paired comparisons (e.g., Baum & Jonides 1979; Evans & Pezdek 1980; Hirtle & Jonides 1985).

An implicit assumption in using distance estimation, particularly in conjunction with MDS, is that one may characterize the internal representation of space in a two dimensional, continuous, holistic, picture-like form. Distance estimation as a process acting on that mental representation can then be thought of as a mental scanning of the internal map, yielding behaviors characteristic of an analog code (Kosslyn, Ball, & Reiser 1978; Thorndyke & Hayes-Roth 1981). However, while a map may be an appropriate first approximation, there is a simplicity in considering the representation to be continuous and distance estimation to be a direct task. Surely, given our understanding of other cognitive processing domains, the schemata of space should play an equally important role. Pipkin (1982) offers a robust argument along just these lines, suggesting that geographers recognize the variety of ways in which surface schemata are consciously processed in the course of spatial problem solving.

Direct experimental evidence leads to a similar conclusion. Spatial processing is influenced by hierarchical structure (McNamara, Hardy, & Hirtle,1989; Stevens & Coupe 1978), by reference points (Holyoak & Mah 1982) and by heuristics of perceptual organization (Tversky 1981). Thus, distance estimation could be viewed as a type of problem-solving in which cognitive structures are as important as spatial distance.

As an analogous situation consider the task of mental arithmetic. Mentally adding 2 or 3 digit numbers for most individuals includes both automatic "table look up" (e.g., 9 + 7 is 16) and effortful manipulation (e.g., carry the one). The speed (and accuracy) of performing an arithmetic problem is a function of the processes involved. Likewise in distance estimation, we can immediately generate certain distances while others we need to calculate.

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The analogy would suggest that techniques common to problem-solving, such as protocol analysis (Ericsson & Simon 1984), could prove beneficial in examining distance estimation. Thus, we directed our subjects to produce on-going verbalizations of distance estimation. Our purpose is to delineate specific heuristics used in distance computation, such as time estimation, triangulation, segmentation and the use of reference points, in order to understand the process of distance estimation. Furthermore, we examined the time to make distance estimates as a function of the referentiality and the familiarity of the locations. It is our belief that the time to make distance estimates is longer for nonreference points due to a constructive process rather than merely a difference in familiarity.

We began by collecting norms of national cognitive maps for the subject pool. 200 cities were rated by 60 undergraduates on familiarity and referentiality. These data were then used in construction of the protocol stimulus space for this experiment.

Method

Subjects

Fifteen male and five female undergraduates attending the State University of New York at Albany participated in order to fulfill a course requirement. The session lasted for one hour.

Materials

Sixty city pairs were constructed on the basis of the previous data obtained on referentiality and familiarity of cities. The sample of cities was chosen to represent a broad range of judgments on both the referentiality and familiarity dimensions. These cities were paired in order to form a heterogeneous sample in terms of distance, angle of orientation, and geographical location. The actual distance of the pairs varied from 37 miles to 2553 miles. Each of the sixty city pairs was printed in bold typeface in the center of an index card.

Three arithmetic problems and one physics problem served as practice items. Each practice problem was printed on a separate sheet of paper. Responses were recorded through use of a cassette tape recorder and lapel microphone.

Procedure

Subjects were seated in a sound proof room in front of the papers containing the practice problems. The experimenter read the practice instructions to the subject, which asked the subject to solve problems out loud, rather than work silently. The experimenter read the practice problems as they were presented to the subject.

After completing the four practice problems, the experimenter attached the microphone and read the instructions for the distance estimation task. Subjects were asked to calculate mentally the distance between pairs of cities, giving all answers in miles, while being as accurate as possible. Subjects were told that the cross-country distance is roughly 3000 miles, but were not told any other mileages. The pairs of cities were presented on 3 in x 5 in cards. Subjects were asked to think out loud, describing any steps used in arriving at the distance estimation. The experimenter read the city pairs to the subject on each trial. Index cards were shuffled before presentation to each subject.

Results

The verbal protocols were coded independently by two coders using a common coding scheme. The coding scheme was designed to include a variety of judgment strategies. On the occasion that a judgment did not fit any of the codes, an additional code was established. As a result, twenty different strategies were identified from the protocols. These are listed in Table 1. These strategies were divided into two main classes, level one and level two. Each of the level one strategies could result in a direct numerical estimate, while the level two strategies required additional estimates in order to generate a numerical answer. For example, the strategy Add was classified as a level two strategy, as two or more distances were added together. The subject using Add would need to generate these component distances by using either a level one strategy or another level two strategy. Eventually, each component distance would need to be generated by a level one strategy. Differences in the level of strategy will be examined later.

Our first concern was to make sure that the subject's estimates were reasonable and that in fact they were carrying out the original task of distance estimation. Overall, there was a high correlation between the actual distance and mean distance estimate ($r = .965$, $p < .001$), with subjects showing a slight overestimation. The best-fitting regression line was given by the equation:

Distance Estimate = 1.08 * Actual Distance + 117.36

The correlations for individual subjects were slightly lower, which was to be expected. They ranged from .687 to .953, with a mean of .887 and a standard deviation of .0627.

We then summarized the data by city to see if there were specific strategies with specific pairs of cities. We did this first in a qualitative manner, noting which strategies were most common and noting under which conditions they were used. The use of strategies was not evenly distributed. The predominant strategies were Add, Analogy, Hedge, Ratio, Subtract and Time Retrieval. Choice of strategy was in part based on the distance to be estimated. Time Retrieval was most commonly used with distances up to 400 miles, while Ratios were used most commonly with cross-country distance of 600 miles or more. The other strategies of Add, Hedge, Analogy, and Subtract were evenly distributed across all distances.

Table 1
Heuristics for Distance Estimation

Level 1 strategies			
1.	DR	Direct Retrieval	"I know Boston to NYC is 180 miles"
2.	DRU	Dir. Retr.-Unspecified	"Boston to NYC is 180 miles"
3.	TR	Time Retrieval	"Boston to NYC is 3 hours, or 180 miles"
4.	LD	Limit Distance	"It can't be more than 200 miles"
5.	LT	Limit Time	"It can't be more than 3 hours"
6.	LDG	Limit Distance General	"They're pretty close, say 180 miles"
7.	PR	Prior Reference	"I remember that I said..."
8.	CDU	Compare Dist. Unclear	"Comparing it to the distance across, I'd say..."
Level 2 strategies			
9.	R	Ratio	"That's about halfway across the US"
10.	MULT	Multiplication	"It's about 3 times..."
11.	ADD	Addition	"50 plus 60 is 110"
12.	SUB	Subtraction	"100 minus 30, I'd call it 70"
13.	AD	Analogy-Distinct	"A to B is the same as C to D"
14.	AC	Analogy-Common End	"A to B is the same as A to C"
15.	HA	Hedge-Add	"It's a little more than the distance..."
16.	HS	Hedge-Subtract	"It's a little less than the distance..."
17.	T	Triangulate	Uses two sides of a triangle to calculate the hypotenuse
Miscellaneous Strategies			
18.	/M/	Modify	Subject changes strategy
19.	TR-G	Time Retrieval-Guess	"I guess that Las Vegas is about 5 hours..."
20.	I	Imagery	Subject is explicit about visualizing
21.	U	Unclear	Unable to classify

Add was typical with city pairs in which there is a intermediate reference point. For example, Springfield, Mass. and Atlantic City, NJ span the intermediate location of New York City. Subtract was typical with city pairs in which there is a reference point outside the pair. For example, Las Vegas and New York City were often judged in relationship to Los Angeles or the West Coast. Ratio was typical with long distances in which the cities are well-known, such as Dallas and San Francisco. In this case, the ratio was based on a cross-country distance. Finally, Time Retrieval was typical with short, well-travelled routes, such as Albany to Boston.

The qualitative analysis suggested certain relationships, which were further analyzed using several sources of quantitative data. For each city pair, we measured the response time (RT) between the point in time that the experimenter completed the verbal presentation of the city pairs and the point in time that the subject provided the final distance estimate; the number of intermediate distance estimates used in the computation (INT.EST), the number of extra locations used in the computation (EXT.LOC), and the number of hierarchic levels used in completion of the distance estimation was calculated (LEVELS). Thus, there were 4 different indices of the amount of processing involved in each calculation, RT, INT.EST, EXT.LOC, and LEVELS. Note that INT.EST and EXT.LOC are related, but not identical. A calculation from city A to city B, based on the distance from city A to a new city C, plus the distance from city C to city B, would include one extra location and two intermediate estimates, whereas a calculation from city A to city B, based on the distance from a new city C to new city D, would include two extra locations and one intermediate estimate.

Additional data pertaining to various aspects of the city pairs, not provided by subjects in this experiment, were available for inclusion in the data analysis. Previous data, obtained from different subjects in the same subject pool, had established norms for the referentiality and familiarity of each city. Referentiality referred to the extent to which a city would serve as a useful reference point for locating other cities, while familiarity referred to the extent to which a city was known. The mean referentiality score (MREF) and the mean familiarity score (MFAM) for each city pair were calculated. Finally, the actual distance (AD) was calculated by measuring the straight line distance on a U.S. map.

Table 2
Correlation Matrix Between Quantitative Variable

	AD	DE	RT	INT_EST	EXT_LOC	LEVELS	MREF
DE	.965***						
RT	.042	.075					
INT.EST	.404***	.436***	.321**				
EXT.LOC	.808***	.858***	.309**	.652***			
LEVELS	.621***	.655***	.363**	.758***	.758***		
MREF	-.070	-.047	-.235*	.206	-.135	.022	
MFAM	-.430***	-.430***	-.207	.036	.433***	-.252*	.607***

*$p < .05$
** $p < .01$
*** $p < .001$.

The correlations between these eight values are displayed in Table 2. The results indicate that the response time (RT) did not covary as a function of DE ($r = .075$, n.s.). However, RT did increase as the mean referentiality (MREF) of the city pairs decreased, (r's = -.235, $p < .05$). Not surprisingly, RT increased with the complexity of the calculation, as indicated by INT.EST, EXT.LOC and LEVELS (r's = .321, .309, .363, respectively, $p < .01$). It is interesting to note that the use of extra locations (EXT.LOC) was related to familiarity ($r = -.433, p < .001$), but not to referentiality ($r = -.135$, n.s.). That is to say, if a location is unfamiliar, then the subjects refer to extra locations to create an estimate. In contrast, the number of intermediate estimates (INT.EST) was related to neither the referentiality ($r = .206$, n.s.), nor the familiarity ($r = .036$, n.s.). However, the distance estimates from unfamiliar cities tend to be more complex in terms of the number of levels (LEVELS) in the hierarchy of calculations ($r = -.251, p < .05$).

Finally, we looked at the relationship between level one and level two strategies. Table 3 presents the pairwise frequency data for level one and level two strategies. The cells of the table indicate the number of times that the lower level strategy appeared in conjunction with the higher level strategy. Only frequently chosen strategies were included. These were Direct Retrieval-Unspecified (DRU), Direct Retrieval (DR), and Time Retrieval (TR), which accounted for 516 out of 585 total level one strategies, and Add, Sub, Analogy, Hedge and Ratio, which were the only level two strategies, with 50 or more occurrences.

The 5 x 3 contingency matrix reported in Table 2 was tested for independence of rows and columns using the chi square statistic. The test indicated that the level one and level two strategies are not independent, ($\chi^2(8) = 235.12$, < .001). In order to determine the source of this result, we partitioned data into a series of seven non-independent sub-tables. In order to maintain the experiment-wise error rate at .05, we restricted the error rate to each analysis to .05/7, or approximately .01. The analyses showed that Analogy and Hedge showed identical distribution across the three sub-strategies. Furthermore, Direct Retrieval was most common with Ratio, Hedge and Analogy, while Time Retrieval was most common with Add and Sub (each significant at $p < .001$).

Table 3
Relationship between Level 1 and Level 2 Strategies

	DRU	DR	TR	Total
ADD	87	28	120	235
SUB	26	26	44	96
ANALOGY	6	47	11	64
HEDGE	14	60	19	93
RATIO	10	92	2	104
Total	143	253	196	592

Discussion

In examining distance estimation as a constructive task, we found a limited number of heuristics were used by subjects in generating distances. The choice of heuristics was shown to be related to variables such as the familiarity of locations and the distance to be judged. The time to make a judgment was related, not only to the complexity of the calculation in terms of intermediate estimates and extra locations, but also to the mean referentiality. Furthermore, it was not related to actual distance or the distance estimate. Finally, times were often added and subtracted, yet rarely was ratio of times taken. Distances on the other hand were used for ratios, as well as addition, subtraction and modification. Our goal in conducting this research was to examine closely the distance estimation process. It has been shown that distance estimation is a complex task, dependent on the nature of the comparison and prior knowledge of the subject, rather than a simple dependent measure based on readout from a cognitive map.

We see two implications for this research. First, for researchers who use distance estimation or reaction time of distance estimation, we voice a concern that the output may be more reflective of the complexity of the task rather than an internal cognitive map. Assurances that variables like prominence and familiarity are controlled adequately should be sought. Second, and more important, the analysis of distance estimation has implications for theories of the mental representation of space. There is evidence that familiar locations can be accessed without accessing related reference points, as seen by the fact that extra locations were only chosen for city pairs with low familarity scores, regardless of the referentiality score.

These results suggest that we may need to modify the hierarchical models of cognitive maps proposed over the past few years (e.g., Stevens & Coupe 1978), in favor of a partially hierarchical model (e.g., McNamara 1986). That is to say that any familiar point in a space may have equal access to any other point through the hierarchical nets, which do not necessarily pass through the primary, reference nodes. Therefore, the cognitive map is more like a system of highways in which highways cluster around populous areas, but, in addition, there are bypasses which connect areas to one another. This would be opposed to a model of represented space analogous to an airline route map, in which all cross-country flights pass through a few hub cities. In the later case, it would be impossible to travel from one small city to another small city without going through the hub city. The hierarchies exist in both models, but the equal access model has greater flexibility in choosing relationships. Through examination of protocols, this study provides evidence of an "equal access" hierarchical map. Of course, the evidence presented is correlational in nature and additional experimental work is needed to confirm such a model.

To summarize, we have shown the importance of considering distance estimation to be a constructive task, based on series of heuristics. The choice of heuristics and the time to make a judgment was shown to be related to variables such as the familiarity of locations and the distance to be judged. The advantage of viewing distance estimation as a constructive process rather than a passive readout off an internal map is argued. This point of view leads to a computational approach that suggests a distinct research program in the area of spatial cognition from the experimental agenda put forth thus far, and suggests that knowledge gained in the fields of problem solving, expert decision making, and mental models can be applied in a fruitful manner to the study of cognitive maps.

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