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COGNITIVE SKILL: IMPLICATIONS FOR SPATIAL SKILL IN LARGE-SCALE ENVIRONMENTS

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ABSTRACT

The recent cognitive skills literature is reviewed and several principles of skilled performance are derived. One of the central issues in cognitive skills concerns the organization of knowledge and it was concluded that in a variety of domains spatial knowledge is hierarchically organized. This issue was explored in a map-drawing study and it was found that the most serious errors were due to a normalizing error, an error that is symptomatic of hierarchical organization. It was concluded that normalizing errors in large scale environments are caused by incorrect representations at higher levels in the hierarchy (global errors). Finally, from an information processing analysis of spatial knowledge, the paper addresses the question of what are the cognitive processes underlying cognitive maps and cognitive mapping.

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The central issue addressed in this paper is why some people are better than others at getting around in large-scale environments. In general, people have a wide variety of spatial knowledge about their environment, including the spatial layout of their house, the neighborhood in which they live, the routes they normally travel, and a great deal of other geographical knowledge. This paper will focus on large-scale environments, environments that cannot be viewed from a single vantage point. In these environments, much of the spatial knowledge has to be inferred rather than perceived.

This paper will take an information-processing approach to the analysis of spatial cognition. From an information-processing point of view, the important theoretical question reduces to how people represent large-scale environments, and what processes they use to operate on this knowledge. That is, what kind of spatial knowledge is stored in memory, and how is it used? Map reading is one example of people's usage of spatial knowledge. In order to understand a specific skill such as map reading, there are some additional complications concerning how people extract knowledge from maps to orient themselves in their environment. However, the central issue underlying map reading still remains one of knowledge representation.

In the analysis of spatial skills in large-scale environments, the paper will touch on three main topics. The first topic will be a review of the literature on cognitive skills. Given the cognitive skills literature, what can we expect to find in spatial skills? The second part of the paper contains an experimental analysis of a common type of spatial error in map drawing, an error that has important implications for how spatial knowledge is represented. The final section of the paper discusses the question of how cognitive maps are represented in memory in the light of the information-processing analysis of spatial skills.

Cognitive Skills

Chess and Other Game Skills

Probably the most relevant literature on visual-spatial skills is the research on skilled chess players. The early work on chess skill was done some 40 years ago, just prior to World War II, by Adrian de Groot (1965, 1966), who was able to study some of the very best chess players in the world, including two World Champions. The basic procedure that de Groot used was to present his subjects with a chess position and ask them to find the best move, and while they were about it, to think aloud. De Groot hoped to discover the source of chess expertise by analyzing these thinking aloud protocols. From his analysis, de Groot was able to dispel a few misconceptions. For example, Masters do not seem to search through the set of possible moves any faster than weaker players, nor do they "see" any further ahead than weaker players. In fact, if anything, chess Masters consider fewer possible moves than weaker players, and they analyze these moves to a lesser depth than weaker players. Typically, a Master might consider 30-50 moves in a difficult position, and search to a depth of 2 or 3 moves. It is unusual for a Master to consider more than 100 moves or search further ahead than 5 moves, and this is true of weaker players also. Thus, both Masters and weaker players search through a very small subset of the possible moves. Further, chess Masters and weaker players both use the same search strategies (depth first with progressive deepening). The one reliable difference between the Masters and the weaker players was that the Masters spent most of their time thinking about the consequences of good moves, whereas the weaker players spent a considerable amount of time analyzing bad moves. However, de Groot was unable to pinpoint the source of chess skill in the verbal protocols.

De Groot did, however, find a very striking difference between Masters

and weaker players in a very different kind of task. He found that when chess Masters were shown a chess position for a very brief interval of time (5 to 10 seconds), they were able to recall the position almost perfectly from memory. Further, this remarkable ability dropped off very rapidly below the Master level. This result cannot be attributed to any kind of superior visual short-term memory capacity of the Masters because when the pieces are placed randomly on the chess board, recall is equally poor for Masters and weaker players (Chase & Simon, 1973a). Chess Masters have the same short-term memory limitations as everyone else.

What is it about this visual memory task that distinguishes Masters from weaker players? The fast presentation in this task eliminates any kind of complex analysis, and performance must rely on very fast recognition processes. What is the chess Master seeing when he looks at the chess board? In theory, the chess Master is seeing familiar patterns of pieces that he recognizes from experience, patterns that simply do not exist in the minds of less experienced and less skilled players. In a series of experiments, Chase and Simon (1973a,b) set out to isolate and analyze the cognitive mechanisms underlying performance in this task, and the first step was to devise a way to isolate these patterns. In these studies, two procedures were used. One procedure was simply to record, on video tape, the placement of pieces in the visual memory task, and then use the pauses during recall to segment the output into patterns. The second procedure was to have the subjects view a chess position in plain sight and reproduce the configuration on an adjacent chess board. In this second procedure, the subject was also video taped, and his head turns were used to segment the output into patterns.

Both of these procedures worked very well. Chess players did not recall whole positions in one smooth series of placements; rather, they recalled chess pieces in rapid bursts followed by long pauses (generally longer than 2 sec). Similarly, when chess players reproduced a position in plain sight, they

did so pattern by pattern with glances at the board position between patterns. Further, there was very good agreement between the two procedures as to what these patterns were.

When the Master's patterns were analyzed in detail, it turned out that he was remembering, for the most part, highly familiar, stereotyped patterns that he sees every day in his play and study of chess. Further, these patterns were very local in nature. That is, they consisted of circumscribed clusters of pieces in very localized regions of the chess board, and the pieces within a pattern were interrelated both by visual features (same color, proximity) and by chess function features (attack, defense). What was surprising about these patterns was how restricted they were, restricted both in terms of their visual-spatial properties and in terms of their stereotypy.

When memory performance was reanalyzed in terms of these patterns, it turned out that both the Master and the weaker players were recalling the same types of patterns, but that the Master's patterns were larger. When patterns are counted rather than pieces, the Master's short-term memory recall is not so different from the novice's. On the same chess position, the Master recalled 20-30 pieces, divided into 6 or more patterns with 3-6 pieces per pattern, whereas the novice recalled only 4-6 pieces, and the novice's patterns consisted of single pieces.

In their theoretical account of chess expertise, Chase and Simon (1973a,b) supposed that the chess Master has a very large repertoire of these patterns in long-term memory that he can quickly recognize, and that both Masters and weaker players are subject to the same severe short-term memory limitations. How many such patterns does the chess Master have in long-term memory? Simon and Chase (1973) considered several independent ways to estimate the size of the Master's pattern vocabulary, and they came up with an estimate of roughly 50,000 different configurations. In contrast, a good club player (Class A) seems to have a recognition vocabulary of about

1,000 patterns, and a novice doesn't seem to recognize any patterns. Fifty thousand patterns seems like a large number, but if one considers how much time a chess Master has spent looking at chess positions (10,000-50,000 hours versus 1,000-5,000 hours of practice for a good club player), 50,000 patterns is not an unreasonable estimate because with similar levels of practice, good readers build up comparable recognition vocabularies for words.

The differences found so far between Masters and weaker players reveal differences in memory organization of chess knowledge. How does this difference relate to the selection of moves? Chase and Simon (1973b) found other differences between Masters and weaker players that may address this issue. In one series of experiments, they found that the Master had a remarkable memory for a series of moves from a position, and indeed, the Master seemed to be able to remember a whole game after seeing the moves once at a rapid rate (5 sec/move). Further, the Master's recall of move sequences showed the same characteristic clustering as his recall of positions: moves were remembered in bursts segmented by pauses, and the pauses seemed to come at breaks between sequences of stereotyped moves. In another experiment, the Master was extremely fast at executing a Knight's Tour puzzle as compared to weaker players. In this puzzle, the task is to move a knight from square to square over a certain prescribed path. The Master's superior performance seemed to be related to his ability to perceive very rapidly the pattern of squares available to the knight. These results suggest that the selection of good moves occurs because good moves are associated with these patterns stored in long-term memory, or in some circumstances, patterns are simply associated with good or bad evaluations. For example, in the Knight's Tour task, the Master is able to find the move for the knight quickly because the pattern of squares available to the knight is associated with certain moves. Likewise, clusters of pieces forming patterns can also

elicit potential (localized) moves. However, in order to understand the selection of moves with respect to the entire board position, we need to postulate that the clusters themselves form configurations of higher level patterns. And it is this configuration of larger regions of the chess board that may elicit sequences of moves, resulting in the segmentation of move sequences during recall.

This view of the organization of chess knowledge suggests that there are hierarchical orders of patterns in memory. That is, not only does the Master have localized structures of 2-6 pieces, but he also may have familiar configurations of chess board positions consisting of several patterns. Although there is no direct evidence regarding the composition of the board patterns and their relation to the generation of good moves, it seems clear that chess expertise resides in the rapid "perceptual" recognition processes that tap the chess master's long-term knowledge base. The if-then kind of logical processing that is revealed from de Groot's analysis of verbal protocols probably reflects relatively late mental operations on the output of the skilled "perceptual" recognition processes. Hence, the Master's expertise does not seem to lie in the slow, conscious, analytical processes that are apparent in verbal protocols. Contrary to popular opinion, the chess Master is a superior recognizer rather than a deep thinker.

This theoretical view can explain several phenomenal feats of the Master. First, the existence of familiar patterns, both at the localized level and at the higher board level, considerably reduces the processing load required for finding the best move because the outcomes have been stored in long-term memory for immediate access rather than having to be discovered through time-consuming and costly analytic search. Second, this also explains why the chess Master seems to think of the best move, or at least a very good one, before he has had the time to analyze the consequences of it. And finally, it explains how a chess Master is able to defeat dozens of weaker

players in simultaneous play because for the most part he simply relies on his pattern recognition abilities--his so called "chess intuition"--to generate potentially good moves.

This analysis of chess skill is consistent with the rest of the literature on game skills. The visual-memory effect with skilled chess players has been replicated many times (Charness, 1976; Ellis, 1973; Frey & Adelman, 1976; Goldin, 1978, 1979; Lane & Robertson, 1979), even with children (Chi, 1978). Further, the same effect has been found with experts in the games of go, gomoku and bridge. In one study, Reitman (1976) was able to study the best non-Oriental go player in the world, and this player's perceptual memory performance with go patterns was virtually identical to that of the chess Masters. In another study, Eisenstadt and Kareev (1975) compared go and gomoku players on the very same patterns. Go and gomoku are played on the same lattice-like board with black and white stones, but the objects of the games are very different and the types of patterns that occur are also very different. (In go, the object is to surround the opponent's stones, whereas in gomoku, the object is to place 5 stones in a row.) Eisenstadt and Kareev (1975) showed that people who were trained to play go had superior memory for a briefly presented pattern taken from a game of go, but they did poorly on patterns taken from a gomoku game. And they found just the reverse for the people they trained to play gomoku.

Non-Perceptual Domains

We often refer to chess Master's expertise as one involving rapid "perceptual" recognition. It is important to ask how "perceptual" is this recognition system? By using the term "perceptual," we only mean it as a contrast with analytical. The recognition system is "perceptual" only to the extent that there is a direct association between the pattern configurations and the potential moves. It is not "perceptual" in the sense of being

necessarily visual. For example, the chess Master can exhibit the same phenomenal memory feats even when the chess board is presented to him as a string of verbal statements. Similarly, one can examine another domain, such as the game of bridge, where there is no obvious spatial component. Nevertheless, the research on bridge expertise has revealed the same visual memory phenomenon. Charness (1979) and Engle and Bukstel (1978) have both reported that bridge experts--those who have spent years playing tournament bridge and have mastered the game--can remember an organized bridge hand almost perfectly after viewing it for a few seconds. With *unorganized hands, performance is uniformly poor for the experts and the less experienced players*. In addition, bridge experts were able to generate bids faster and more accurately, they planned the play of a hand faster and more accurately, and they had superior memory for hands they had played. Both articles concluded that bridge expertise, like chess, also depends upon long-term knowledge, and that expertise depends upon fast-access pattern recognition because these patterns are associated with strategies and correct lines of play.

In a totally different domain, physics problem solving, research is forthcoming that shows some effects analogous to those found in chess and related games, even though non-memory tasks were used. That is, Simon and Simon (1978) and Larkin, McDermott, Simon and Simon (in press) have discussed the phenomenon of "physical intuition," much like the chess Master's "chess intuition." Physical intuition is the capacity of the expert physicist to solve difficult problems rapidly, without a great deal of conscious deliberation, much like the non-analytical nature of the chess Master's perceptual ability to find good moves. In a series of ongoing studies, the mechanisms underlying this physical intuition are beginning to emerge. Using a categorization task, Chi and Glaser (1979) have found that expert physicists group physics problems as similar according to the underlying principles (e.g.,

Newton's Second Law) whereas novices group problems as similar according to the physical entities contained in the problems (e.g. a spring or an incline plane problem). This ability to categorize problems rapidly (45 sec per problem, including reading time) suggests that there exists schemata of problem types, much like those found for algebra word problems (Hinsley, Hayes & Simon, 1977). The most revealing finding, however, is that experts' schemata are organized around central physics principles, whereas the novices' schemata are organized around physical entities or objects. Furthermore, Chi, Feltovich and Glaser (1979) are beginning to identify patterns of cues in the problem statements that can elicit directly the relevant underlying physics principles that should be applied to solve a given problem. Once a relevant schema is activated from the pattern of cues in the problem statement, the expert physicist can then proceed to work top-down in a more analytical manner within the activated schema, to search for the appropriate procedure for solving a particular problem.

These physics results suggest the existence of a rapid perceptual mechanism for problem solving, not unlike the chess Master's ability to think of the good moves immediately followed by more analytical search. Hence, the extraordinary visual memory phenomenon of the chess Masters reflects not so much the perceptual nature of "intuition," but rather, the knowledge and the organization of this knowledge that can facilitate his ability to have a rapid "understanding" of the chess situation. Good understanding, according to Greeno (1977) is the ability of a problem solver to construct an adequate representation of the problem. The adequacy of an initial problem representation (that may be responsible for physical intuition) clearly depends on the nature and organization of the knowledge existing in memory. The fact that the expert physicist has a more coherent, complete, and principle-oriented representation of physics knowledge, necessarily implies that his initial understanding of the physics problem must necessarily be

better, leading more easily to a correct solution.

Higher-Level Organization

We have alluded earlier to the possibility that chess Masters may have higher-level configurations. Although Chase and Simon (1973a, b) did not analyze the higher-level organization of chess patterns in any detail, they did report some evidence for between-pattern links based on conceptual and strategic aspects of the game (mostly coordinated attacks by patterns of pieces).

There are now stronger results relevant to this particular issue. Akin (1980) has analyzed the recall of building plans by architects and found several interesting results. First, as with chess players, architects do not draw architectural plans from memory in one smooth output. Rather, architects recall plans pattern by pattern, and Akin was able to describe the nature of these patterns. Second, architectural plans are recalled hierarchically. That is, from an analysis of the pauses in recall, the nature of the elements recalled, and the order in which they were recalled, Akin was able to determine that these patterns were organized hierarchically with several levels. This is a very important property, and it should be further pointed out that a hierarchy is not universally the case. For example, Akin was able to show that under some circumstances in which the drawings were poorly encoded, the memory organization was less hierarchical and more fragmented, taking on more the property of a lattice than a tree structure. Finally, Akin was able to describe the nature of these patterns. At the lowest level in the hierarchy, these patterns are fairly small parts of functional spaces, such as wall segments, doors, table in a corner, etc. The next higher level in the hierarchy contains rooms and other areas, and higher levels contain clusters of rooms or areas.

It is interesting to note that the fairly localized property of architectural patterns at the lowest level in the hierarchy is reminiscent of the localized

nature of chess patterns. It is only at the next level in the hierarchy that architectural drawings take on the functional form of the architectural space: rooms, halls, etc. It seems that architectural patterns are similar to chess patterns in that functional properties are more important at higher levels while structural properties are more important at lower levels. What is striking about both the architectural and chess patterns is that at the lowest level, the memory representations are very localized.

Similarly, Egan and Schwartz (1979) have analyzed the recall of circuit diagrams by expert electronics technicians after a brief exposure (5-15 sec) of the diagram. Egan and Schwartz reported the same visual memory effect, and they also found evidence of a higher-level organization for the skilled electronics technician. At the lowest level, the basic patterns were very similar to the chess patterns and architectural patterns in terms of their localized nature. The skilled technicians, however, were faster and more accurate with their between-pattern recall than the novices, which is good evidence in favor of higher-level organization. As Egan and Schwartz point out, to aid their recall, skilled technicians use their conceptual knowledge of what function the circuit was designed for. This is precisely the point that Akin made with respect to higher-level organization in the recall of building plans by architects. It is not yet clear, however, whether this higher-level organization of circuit diagrams is best described as a hierarchical tree structure or a flatter lattice-like structure.

Analogous results are also emerging from research on physics problem solving. Chi, Feltovich, and Glaser (1979) are finding that physics knowledge can be organized at several levels. The lowest level contains "structural" or "physical" properties of the problem situation, such as a spring, a pulley, or an incline plane. The next higher level contains more complex situations that are usually not directly described in problem statements, such as a "before and after" situation. This refers to the states of energy or momentum of the

total system before and after an event. The highest level of knowledge contains basic physics principles and procedures for their application. Expert physicists have elaborate knowledge at all levels, but their organization revolves around the principles, and their processing tends to be top-down. Novices have only developed elaborate knowledge structure of the lowest level, such as the relations among objects in an incline plane situation. Their processing of problem situations appears to be more bottom-up.

The existence of higher-level functional knowledge in the more experienced individuals has also been demonstrated in the domain of baseball. Chiesi, Spilich, and Voss (1979) have found that the differential recall of baseball events by individuals with high- and low-baseball knowledge can be traced to their differential ability to relate the events to the game's goal structure. That is, high- and low-knowledge individuals are equally competent at recalling single sentences of domain-related information. However, high-knowledge individuals are better at recalling sequences of baseball events, presumably because they are better able to relate each sequence to the game's hierarchical goal structure of winning, scoring runs, and advancing runners.

To sum up the analysis so far, it appears that a large long-term knowledge base underlies skill performance in several varieties of spatial (as well as non-spatial) domains. Further, a very important component of the knowledge base is a fast-access pattern recognition system, a system that greatly reduces processing load. In the game-playing examples and in physics problem solving, these patterns serve the purpose of retrieval aids for desirable courses of action. In the case of architects and electronics technicians, these patterns facilitate the perceptual organization of architectural drawings and circuit diagrams respectively. What is striking among all these domains is the similarity in the hierarchical nature of the organization of knowledge. At the lowest level, the memory representations

are very localized, containing "structural" properties, whereas at the higher levels, functional properties are more important.

Development of Cognitive Skill

It is important to ask how expertise is acquired in a given domain. The most obvious answer is practice, thousands of hours of practice, because it takes such a long time to acquire the necessary knowledge base. There may be some as yet undiscovered basic abilities that underlie the attainment of truly exceptional performance, such as a Grandmaster in chess. But for the most part, practice is by far the best predictor of performance in a majority of cases.

Practice can produce two kinds of knowledge. Practice enables the learner to build up a storage of patterns or lexicons. It can simultaneously also produce a set of strategies (or procedures) that can operate on the patterns. The presence of both types of knowledge can be demonstrated by examining exceptional mental calculators. Professor A.C. Aitken, for example, was perhaps the world's most skilled mental calculation wizard. Hunter (1968) was able to show that Aitken's skill was primarily the result of two types of long-term memory knowledge. First, he possessed a tremendous amount of lexical knowledge about the properties of numbers. For example, he could "instantly" name the factors of any number up to 1,500. Thus, for Aitken, all the 3-digit numbers and a few 4-digit numbers were unique and semantically rich, whereas for most of us, this is true only for the digits and a few other numbers, such as one's age. This knowledge alone provides a very substantial reduction in the memory load during mental calculation. Second, Aitken had gradually acquired a large variety of computational procedures designed to reduce the memory load in mental calculations. With years of intensive practice, these computational procedures gradually became faster and more automatic, to the point where Aitken's computational skills were

truly astounding. For normal people, mental computations are severely limited by the capacity of short-term memory, and this limit is further compounded by the fact that most of us are taught only a few procedures that have very substantial storage overheads. For problems of any complexity, normal people have to resort to paper and pencil aids in order to store the results of intermediate computations. Professor Aitken (as well as other lightning calculators) gradually built up a long-term knowledge system that was capable of bypassing these constraints.

The acquisition of both types of knowledge can also be seen by tracing their development with time. Rayner (1958) analyzed the performance of six beginning players over a 5-week period as they learned the game of gomoku. He was able to describe the types of patterns that the players eventually learned to look for and the strategies dictated by each pattern. The patterns themselves are visually quite simple; the complexity arises in the number of moves required by the strategy to generate a win. The most complicated strategy that Rayner described was an 11-move sequence triggered by a fairly simple and innocuous-looking pattern of four stones. In his analysis of gomoku, Rayner described a process in which his subjects gradually switched from an analytic mode of working through the strategies to a perceptual mode in which they searched for familiar patterns for which they had already learned a winning strategy. In short, Rayner analyzed experimentally in the laboratory over a 5-week period, the perceptual learning process that is presumed to occur on a grand scale, over the course of years of practice, with the chess Masters.

The acquisition of both types of knowledge can be manipulated independently. In an ongoing study, Chase and Ericsson (1978) were able to increase the memory span for digits of an average college student from 7 to 70 digits over a course of one year. How did this subject (S.F.) increase his digit span with practice? As it turns out, S.F. has a large knowledge base of

running times for various races (e.g., 349 - three minutes and forty-nine seconds, near world-record mile time). Practice in this case, did not produce the large data base of lexicons of running times. What the subject did with practice was to develop an elaborate mnemonic system where he groups and segments the digits into hierarchical groups. In fact, unless he continually develops new hierarchical groups to code the digits, he would not be able to increase his digit span. Hence, this research suggests the following. First, the subject can independently develop a set of strategies to code and recall digits, where the digit patterns are already stored in memory. Second, there seems to be no limit to the extent to which his memory span can be increased with extended practice. Finally, these data again reinforce the notion that memory span limitation and short-term memory capacity are not synonymous. Memory span is limited both by the capacity of short-term memory and by the coding process. The more elaborate the coding processes a subject can develop, the greater will be the discrepancy between memory span and short-term memory capacity.

The three studies just cited suggest that cognitive skill acquisition involves the development of extensive lexical and procedural knowledge. Such knowledge structures can take either the form of abstract-symbolic information (as in digits) or visual spatial characteristics (such as a pattern of stones). Further, the principal mechanism underlying the development of such skill is extensive practice to build up the long-term knowledge base. And finally, there appears to be no limit to the extent to which cognitive skills can be developed, except perhaps for physiological processes such as aging. Elo (1965), for example, has computed an objective measure of tournament performance in world-class chess players, and has found a very regular function when this performance is plotted as a function of age. There is a steady, rapid improvement in performance from around age 14 through the 20's, followed by a peak at around age 35. Thereafter, there is a slow, regular

decline in performance until, at age 65, performance has deteriorated to the same level as a 21-year-old.

It is perhaps instructive to review the major findings of the perceptual-motor skills literature to see what it can tell us about skill acquisition and cognitive skills. Probably the two most important generalizations to come out of that literature are (1) the continuous nature of skill acquisition, and (2) the specificity of acquired skills. If one looks at skilled performance as a function of practice, there seems to be a very lawful relation. Major gains in performance occur early in practice, followed by slower, steady gains over extended periods of practice. For a large number of speeded skills, if practice time and performance time are both transformed into logarithmic scales, the function seems to be linear. This result has led to mathematical theories of the learning process which assume independent changes in a very large number of memory elements (Crossman, 1959; Lewis, 1978). Some such lawful relation is to be expected if skill acquisition involves a very large number of additions and modifications to the knowledge base.

Besides the smoothness of the learning curve, it is very surprising that improvements in less complex skills still occur after years of practice. In one industrial study, Crossman (1956) found a steady improvement over a 2-year period in the speed with which workers could operate a cigar-making machine. Beyond 2 years, the apparent asymptote in the workers' speed actually turned out to be a limit in the cycle time of the machine. What is really surprising about this study is that a seemingly simple motor skill, such a cigar-making, can continue to show improvement with years of practice.

The continuous nature of motor skill acquisition parallels the lack of any asymptotic limit to achievements in complex cognitive domains, such as mnemonic skills in digit span, mental calculations, and chess. It is typical to see steady improvements with years of practice. The only real limits seem to be a result of physiological limits such as aging.

The second important generalization from the perceptual-motor skills literature is that skills are so specific. That is, it has not been possible to predict individual differences in acquisition of complex perceptual-motor skills even in the face of large and reliable individual differences on those skills. This is true both from basic abilities and from other skills. That is, it has not been possible to predict performance on tennis, say, either from measuring the obvious basic abilities like eye-hand coordination, quickness, etc., or from measuring performance on another closely related skill, say, raquetball (Fitts & Posner, 1967; Marteniuk, 1974; Singer, 1968). The best predictor of future performance is present performance level. But even so, predicting performance at advanced levels from beginning levels of performance is not very reliable, presumably because, as Fleishman (1966) has shown, during the course of skill acquisition, there is systematic shifting of factors responsible for skilled performance. Presumably, at extremely advanced levels of skill, performance becomes more dependent upon the contents of the knowledge base.

Both of these phenomena--the continuous improvement over long periods and skill specificity--are not unique to perceptual-motor skills. They also seem to be characteristic of cognitive skills, and for a very good theoretical reason. (There is not, in fact, much theoretical justification for differentiating perceptual-motor and cognitive skills.) Performance at high levels of a skill is so dependent on a vast knowledge base of specific information about that particular skill. That is why practice is the major independent variable--because it simply takes so long to acquire the knowledge base--and transfer to other skills is for the most part ruled out because of the specificity of the knowledge.

At this point, the paper has considered several principles of skilled performance. What seems to be common to all skills is the acquisition of knowledge in long-term memory, the purpose of which is to reduce processing

load. A large component of this knowledge is visual-spatial pattern recognition because these patterns serve as retrieval cues for appropriate action. In the next section, skill differences in map drawing are analyzed in terms of how long-term knowledge is organized, and the final section considers the question of how spatial skills in large-scale environments are organized.

Map Drawing

In this study the phenomenon of interest is a revealing type of spatial error that often occurs when people draw maps. This error is interesting because it belongs to a class of normalizing errors that occur in large-scale environments, and an argument will be made that these normalizing errors are the result of hierarchical organization of the memory representation.

Sixteen college students were asked to draw a map of the Carnegie-Mellon University campus, including 18 well-known buildings and street intersections. The sixteen students consisted of 11 architecture undergraduates and 5 other undergraduates.

In order to eliminate problems associated with idiosyncratic drawing scales, each person's map was standardized in the x and y dimensions separately, and all subsequent analyses were based on z-scores. This transformation preserves individual distortions, but it does not allow differences in scale to enter into group averages.

Insert Figures 1 and 2 about here

Figures 1 and 2 show the average maps for architects and nonarchitects separately. The actual locations of the campus buildings are indicated by the squares, and the actual location of the roads surrounding the campus are also shown. The circles represent the average recalled location of the buildings in the subjects' maps, and the brackets at each location are ± 1 standard

deviation between subjects in the x and y dimensions, separately. The dashed lines depict the errors--the discrepancy between the actual locations and the average drawn locations--and the legend contains the Root Mean Squared Deviation (RMSD), which is the standard deviation of these errors. There are three things to notice about these maps. (1) architects were significantly more accurate than nonarchitects (compare the RMSDs); (2) with one important exception, both architects and nonarchitects were very accurate in their placements, and (3) the one important exception involves an intersection of two streets that are not rectilinear with respect to the rest of the environment. The standard deviation for this one location was enormously large, as compared to the other locations. A closer examination of the individual maps revealed the source of the error. Most of the subjects (12) drew the streets of this intersection at right angles with respect to the rest of the environment, and they did so by forcing a 90° turn in one street or the other. Only four subjects, all architects, correctly drew these two streets at a 45° angle with respect to the rest of the environment.

Insert Figure 3 about here

Figure 3 compares the actual street intersections with the three types of subjects. First, notice that the very large error in the location of the intersection (Figs. 1 & 2) is an averaging artifact caused by the mixture of the three types of subjects in the figure. Second, even the map of the subjects who drew the intersection correctly is more rectilinear than the real map. Finally, a closer examination of Figures 1 and 2 reveals systematic distortions at other campus locations. Most of the cases where the reported location is more than 1 standard deviation away from the true location are situations in which the reported location is distorted toward a more rectilinear arrangement.

This error, it is argued, belongs to a class of normalizing errors that are

the result of hierarchical organization of spatial knowledge. In this case, it appears that these errors are the result of a grid structure that people impose on their memory representations, and this grid structure can cause distortions in the location of local regions. Theoretically, it is assumed that people organize their geographical knowledge into sets of localized regions, and that these regions are organized hierarchically by a set of more global relations that link the more local regions together. For example, most people's geographical knowledge contains such relations as California is west of Nevada. In the present case, it is assumed that in the absence of specific global features, particularly in an urban environment, people automatically assume a rectilinear grid structure. This is precisely the assumption that Kuipers (1978) made in his elaborate formal model of spatial knowledge. There are a few instances of this type of error reported elsewhere in the literature. In one very interesting study, Milgram and Jodelet (1976) analyzed the handdrawn maps of Paris by 218 Parisians, and they reported that over 90% of their subjects underestimated the actual curvature of the Seine River. With the possible exception of the city limits of Paris, the Seine is probably the most prominent global feature of Paris. As Figure 4 illustrates, however, in most people's minds the Seine describes a more gentle and more regular curved path through Paris than is actually the case. Milgram and Jodelet conclude that this error

...reflects the subjects' experience. Although the Alma bend of the Seine is apparent in high aerial views of the city, it is not experienced as a sharp curve in the ordinary walk or drive through the city. The curve is extended over a sufficient distance so that the pronounced turn of the river is obscured. (p.109).

They further point out that since the Seine is usually drawn first, it introduces distortions in the locations of local regions, sometimes incorrectly displacing regions to the wrong side of the river or even eliminating certain districts altogether. In his informal interviews, Kuipers (1977) has also reported similar kinds of distortions caused by the curvature of the Charles River in Boston.

Insert Figure 4 about here

In the case of Paris, it is assumed that a prominent feature like the Seine River is used as a global (hierarchical) feature, and local regions are represented with respect to this global feature. As Milgram and Jodelet point out, people generally notice the curvature, but they fail to notice the irregularity, and the result is that they normalize the curvature in their memory representations. This kind of normalization can then serve as a serious source of error because people then incorrectly represent the relative locations of districts with respect to the more global feature. Notice the important implications of this assumption--that local regions are represented with respect to more global features: a great deal of spatial knowledge, perhaps most, is inferred. The relationship between two districts, say, is derived from their individual relationships to a global feature.

In another interesting study, Stevens and Coupe (1978) asked people to indicate the direction from one city to another, and they discovered several instances of large normalizing errors. In one particularly cogent example, they asked people who lived in San Diego to indicate the direction of Reno, Nevada. Virtually everyone indicated that Reno lies northeast of San Diego, when in fact it is northwest. As Stevens and Coupe point out, this type of error is symptomatic of hierarchical representation of spatial knowledge. To explain this error, it is assumed that people normally retrieve a set of spatial relations of the following sort from long-term memory:

- (a) Nevada is east of California.
- (b) San Diego is in the Southern part of California on the West coast.
- (c) Reno is in the Central part of Nevada on the California border.

And given this set of spatial relations, people infer that Reno is northeast of

San Diego. These relations need not be verbal; most cognitive theorists would probably make the claim that spatial relations are abstract propositions (c.f. Clark & Chase, 1972). However, for the present purposes, the claim is simply that spatial knowledge is organized hierarchically without making any claims about the format. It is important to point out that even if one believes that spatial knowledge is stored as analog images, this kind of spatial error is still the result of hierarchical representations. That is, suppose that an analog image of California and Nevada is constructed in the mind's eye, and the relation of San Diego and Reno is "perceived" off the image. Still, the spatial knowledge needed to construct the image must come from somewhere; according to Kosslyn and Schwartz (1977), it must come from more abstract knowledge in long-term memory, from some kind of deep-structure representation of the sort illustrated in the above three spatial relations (a,b and c). Regardless of whether the inferencing process is analog or propositional, the strong claim is made here that the long-term memory representation is hierarchical. If spatial knowledge were not hierarchical in this case--if, say, the relationship between San Diego and Reno were stored directly--this kind of error would not occur.

Before moving on to the next topic, a couple of questions need to be addressed. First, why should spatial knowledge be hierarchical? The standard answer to this question is twofold. Hierarchies are efficient, and they are well-suited for inference making. With hierarchical representations, it is not necessary to directly store every possible spatial relation; spatial relations that cut across regions can be inferred from more global knowledge. In addition, hierarchies in general are well-suited for making abstractions, generalizations and inferences (Chase, 1978).

A second question is why are these normalizing errors relevant with respect to everyday performance in the real world? That is, people seem to navigate perfectly well in the city without being aware of variations in the

global shapes of the routes they normally travel, as Clayton (in press) and Thorndyke (in press) have both pointed out. If people can get around in their urban environments using known routes, what harm is there in not noticing, for example, that a turn is 45° rather than 90° ? The answer is that sequential knowledge of known routes is very often sufficient to get around. Difficulties can quickly arise, however, if one attempts to use global features for navigation in these circumstances. For example, one can normally go around the block and get back to the same location by making four right turns, but not necessarily in cities like Pittsburgh or Boston! Serious navigational mistakes can also occur if one attempts to get from one neighborhood to the next with incorrect global representations like those in Figure 3. In the present study, it should be pointed out that some of the architects did exhibit superior knowledge of their large scale environments, and this difference reflects real spatial skills. One of our primary research goals is to identify what constitutes spatial skills.

Spatial Knowledge and Cognitive Maps

What kind of spatial knowledge is activated when people think about their environment? This section will attempt to deal with this question, and to explore the implications for cognitive maps. First, there is a substantial literature on this topic, and the reader is referred to several good reviews (Clayton, in press; Hart & Moore, 1973; Siegel & White, 1975; Thorndyke, in press), and for the most complete information processing model of spatial cognition, the reader is referred to Kuiper's (1977, 1978) computer simulation. From a variety of sources in the literature, there is good evidence for the existence of at least two kinds of spatial knowledge. Routes refers to a local sequence of instructions that guides a person from one place to another along a known path. Survey knowledge refers to a more global structure containing a network of spatial relations that organizes more local regions. For example,

if one knew that a desired location was to the north, say, of a prominent landmark, then a person's survey knowledge would allow one to get there without ever having traveled that route. From the developmental literature, it appears that there is an orderly progression in children's representations of large-scale environments with at least one important shift from route-type to survey-type representations, probably at the onset of Piaget's stage of Concrete thought (around age 6). Some people even claim that when adults learn a new area, there is a recapitulation of these developmental stages, such that people first learn routes, and survey representations are subsequently built out of routes. (This latter statement is undoubtedly an oversimplification.)

This distinction between route and survey knowledge seems to be a fundamental one. In terms of performance, survey knowledge keeps people from getting lost when they leave a known route, and in terms of cognitive theory, the development of survey knowledge may be a very important advancement in the nature of representations.

What are some of the properties of this knowledge base? In the previous sections, an argument was made that (spatial) knowledge is hierarchical, and that local regions are interconnected by a network of global features. In the literature, there are also many references to the varied nature of this knowledge. In cities, this survey knowledge often takes the form of a grid structure, or a network of relative spatial relations with respect to some prominent landmark. Another important form of survey knowledge is a coordinate system based on cardinal directions (North, South, East and West). It also seems quite evident that there are multiple frames of reference (coordinate as well as nested). For example, when a person emerges from the subway system onto the street, or a driver gets off an interstate system onto a local street network, there is a shift in the frame of reference.

Given this rich variety of representational knowledge, how is it used?

From an information-processing point of view, what is the other half of the coin: what are the mental processes that people use to operate on these knowledge structures to actually get around in large-scale environments? There is understandably less written about process than structure in the literature, but there are still some good ideas in the literature. The reader is referred to the chapters by Clayton (in press), Thorndyke (in press), and to Kuiper's (1978) article. It is suggested that there is a fundamental distinction between two kinds of processes: automatic procedures and inference rules. In his model of spatial cognition, Kuipers (1978) only makes use of inference rules, but a strong case can be made that people use automatic procedures as well. An automatic procedure is used when someone follows a well-learned route. At each choice point along a well-traveled route, a decision must be made as to which way to go, and this is normally accomplished smoothly, automatically and unconsciously. Nevertheless, people must make use of some information from the environment to follow a route. The usual suggestion is that people use visual "images" or "icons." That is, people have visual knowledge about each choice point stored in long-term memory, and as they approach these choice points, certain visual features serve to activate this knowledge. And associated with this knowledge are procedures that tell people what to do next. This is exactly the argument made earlier as to how chess players can think of good moves, good evaluations, or whole sequences of moves rapidly and seemingly unconsciously. In each case, procedural knowledge is built into long-term recognition memory, and if the right visual information appears, this knowledge is activated and appropriate action is taken.

The second kind of process that people use to operate on their spatial knowledge is the inference rule. In principle, these rules are used to derive knowledge that isn't explicitly stored in memory. They may be used to fill in gaps in routes, to orient oneself in the environment, to perform geometric

problem-solving, and so on; Kuipers (1977, 1978) has provided a taxonomy of various types of inference rules for his model of spatial knowledge. A good example of the use of inference rules is provided by Stevens and Coupe's (1978) task. When a person is asked to indicate the direction of Reno with respect to San Diego, he may or may not be conscious of some momentary mental image of California and Nevada, but in any case, he can easily generate an answer in a very few seconds. According to Stevens and Coupe (1978), people go through an inference process in which they derive the answer from the set of hierarchical propositions described earlier. Although Stevens and Coupe did not specify the inference rules needed to derive the answer, in principle, the types of rules described by Kuipers (1977, 1978) should work.

Given this rather elaborate information-processing theory of spatial knowledge, in what ways is skill manifested? Why are some people better than others at getting around in large-scale environments? From the earlier analysis of the cognitive skills literature, one would have to say that the overriding consideration is the size of the knowledge base. People who have spent more time in a region, and who are more familiar with the area, should perform better. Perhaps a more interesting and less obvious question is why some people acquire spatial knowledge faster or better. That is, holding learning time constant, why are some people still superior? The standard answer in the literature seems to be that some people are better at using survey knowledge; certainly this is true developmentally in terms of why older children are better than younger children at getting around in large scale environments. This was also true in the one skill difference reported in this paper: architects were superior to nonarchitects in their ability to accurately draw a map of their campus, and the biggest skill difference was due to that subset of architects who could correctly depict the global shape of the campus. Clearly, one would be interested in pursuing this issue further to

determine if this performance is the result of some primary spatial ability for which architects are preselected, some aspect of their training, their curiosity about their environment, etc. To summarize this issue, it seems fair to say that since there are many components involved in spatial knowledge, spatial skills could arise in many ways, and a full understanding will require more research.

The final issue to be addressed in this paper is what are the cognitive components of cognitive mapping and cognitive maps. In the introduction to their influential volume, Downs and Stea (1973a) define these terms as follows:

Cognitive mapping is a construct which encompasses those cognitive processes which enable people to acquire, code, store, recall, and manipulate information about the nature of their spatial environment... a cognitive map is an abstraction which refers to a cross-section, at one point in time, of the environment as people believe it to be. (p. xiv).

Thus defined, cognitive mapping is a good description for a cognitive model of spatial cognition, and this is precisely what Kuipers (1978) has attempted to implement, and a cognitive map seems like a good way to characterize spatial knowledge. Two related problems, however, have arisen with respect to cognitive maps. One problem is what psychological significance to attach to cognitive maps, and the other problem is the operational difficulty of measuring the cognitive map.

As Downs and Stea (1973b) point out, researchers have tended to assume more psychological significance than is warranted to the cartographic properties of cognitive maps, and this has especially been true of geographers and cartographers. This misconception probably originated from Tolman's (1948) very influential article on cognitive maps. In this article, Tolman effectively dispelled the idea that the spatial behavior of animals (and people) could be explained in terms of stimulus-response connections. In its place, he substituted the notion that "something like a field map gets established in the head...." By his very choice of terms--he entitled his article "Cognitive Maps

in *Rats and Men*--he developed the idea that there exists a two-dimensional map-like image in the head with topological or cartographic properties that people and animals use to navigate through their environment. From what we now know, this map metaphor has to be false. First, it seems clear from the cognitive literature that people do not have anywhere near the capacity to conjure up a complete image of a cognitive map. Certainly, chess Masters cannot imagine a whole chess board at once--they do it pattern-by-pattern. Architects, when drawing a plan from memory, only retrieve small sub-parts at a time, and the same is true of electronic technicians when working with circuit diagrams. In the map drawing study, subjects worked on small sub-parts of maps when they drew maps, and they retrieved routes bit-by-bit. They seem to recall local pieces of routes and maps plus more global information about overall shape. Second, with respect to more permanent long-term memory knowledge, one is talking about vast amounts of knowledge of various kinds, probably organized hierarchically, that can't possibly all appear in a cognitive map. In short, there does not seem to be any memory structure that corresponds to the cognitive map with the properties commonly ascribed to it.

The second problem concerns measuring the cognitive map. Given that a cognitive map is a useful abstraction that captures, at one moment in time, a cross-section of people's perception of their environment, then it should be possible to obtain a "snapshot," so to speak, of this abstraction. This is exactly what Lynch (1960) tried to accomplish in his analysis of people's images of their city. Lynch used sketch maps, lengthy interviews, and field studies, to construct composite maps of three U.S. cities: Boston, Jersey City and Los Angeles. Lynch tried to abstract the key elements--paths, edges, landmarks, nodes, and districts--that were most memorable or imagable. The maps that Lynch constructed are very compelling and they seem to portray the essence and the character of each city. With his method, Lynch has

captured an abstraction, an abstraction that seems to describe how people collectively view their city, how people of different ethnic backgrounds perceive their environments, and how the physical and sociological aspects of a city can affect people's representations of their environment. No wonder that Lynch's technique has had such a large impact on urban research.

But now a word of caution. These sociological maps should not be thought of as psychologically real. As pointed out above, sketch maps or other derived maps cannot be thought of as measures of some internal cognitive map. Nor should they be thought of as aggregate maps. That is, nothing like these maps exist inside the heads of individuals. The averaging process does not somehow derive an "average" cognitive map.

This is an important but subtle point, and it is perhaps best illustrated with an example. In their analysis of sketch maps of Paris, Milgram and Jodelet (1976) plotted the 50 most frequent elements from their 218 subjects, and they found that the frequency of elements closely reflected the tourist Paris, the most famous sites of the city: Seine, Arc de Triomphe, Notre Dame, Tour Eiffel, etc. They therefore conclude that their data do not support the popular notion held by Parisians that there is a real Paris quite apart from the tourist Paris. But if Parisians take pride in the lesser known parts of Paris, especially if the Parisian's Paris is more idiosyncratic, it is not clear how their procedure would detect this aspect of Paris. By listing elements in order of frequency, they have in effect averaged out the private, idiosyncratic parts of individual maps. The net result is a sociological abstraction that is not characteristic of any one individual's sketch map. In this sense, these sociological maps are not psychologically real.

This is not to say that these maps are not useful sociological abstractions. This "averaged" map is undoubtedly a very useful index of the prominent parts of Paris, and as such could be very useful to urbanologists. In fact, these maps have already been demonstrated to be very useful research

devices. It should simply be pointed out that the real psychological processes underlying spatial cognition reside in the short-term and long-term knowledge structures and processes described previously.

Summary

This paper has attempted to define the nature of spatial skill in large-scale environments. The first section of the paper contained an analysis of cognitive skills in a variety of domains, and several characteristics of skill were revealed. One important characteristic of skills is that with practice there is a shift from analytic reasoning to fast-access recognition processes, and this shift seems to be an inevitable result of severe short-term memory limitations. That is, analytic reasoning places too heavy a burden on short-term memory, and hence performance is serial and slow. To perform skills rapidly and efficiently requires ready access to large amounts of task-specific knowledge. People gradually acquire "pre-programmed" knowledge, knowledge that can guide skilled performance smoothly and efficiently without overloading short-term memory once it is triggered by the recognition system.

Another important characteristic of skills is the nature of this knowledge representation. It seems to be true for a wide variety of cognitive skills that knowledge is organized hierarchically. For visual-spatial skills, and perhaps for other skills as well, at the lowest level in the hierarchy, knowledge seems to be organized in very localized and stereotyped patterns. At higher levels, these local patterns are organized together by means of more conceptual or functional properties.

An analysis of the spatial skills literature revealed that large-scale environments are generally thought of as hierarchically organized. People seem to have at least two distinct kinds of spatial knowledge: routes and survey knowledge. Further, there is very good evidence that geographic

knowledge is organized in much the same way as other spatial skills, with local regions organized hierarchically around more global features. In cities, the hierarchy often takes the form of a grid structure. In one map-drawing study, it was found that skilled subjects were less likely to make normalizing errors on the hierarchical grid structure: in an environment which deviates from the grid structure, they were more likely to correctly code the deviation. This normalizing error, as well as other similar errors reported in the literature, is taken as strong evidence that geographical knowledge is organized hierarchically.

One final issue concerns the nature of cognitive maps. It was suggested that there is no cognitive structure corresponding to a "map in the head," as Tolman (1948) had originally supposed. From our analysis of cognitive skills, it was suggested that there is not enough short-term memory capacity to support an image of a map, and the vast, hierarchical long-term knowledge structures certainly are not organized like a map. The map metaphor is not a good model of how people organize their spatial knowledge.

One final word of caution. Cognitive mapping studies are a useful research technique for deriving sociological abstractions for urbanologists, but these "averaged" maps should not be thought of as psychological structures.

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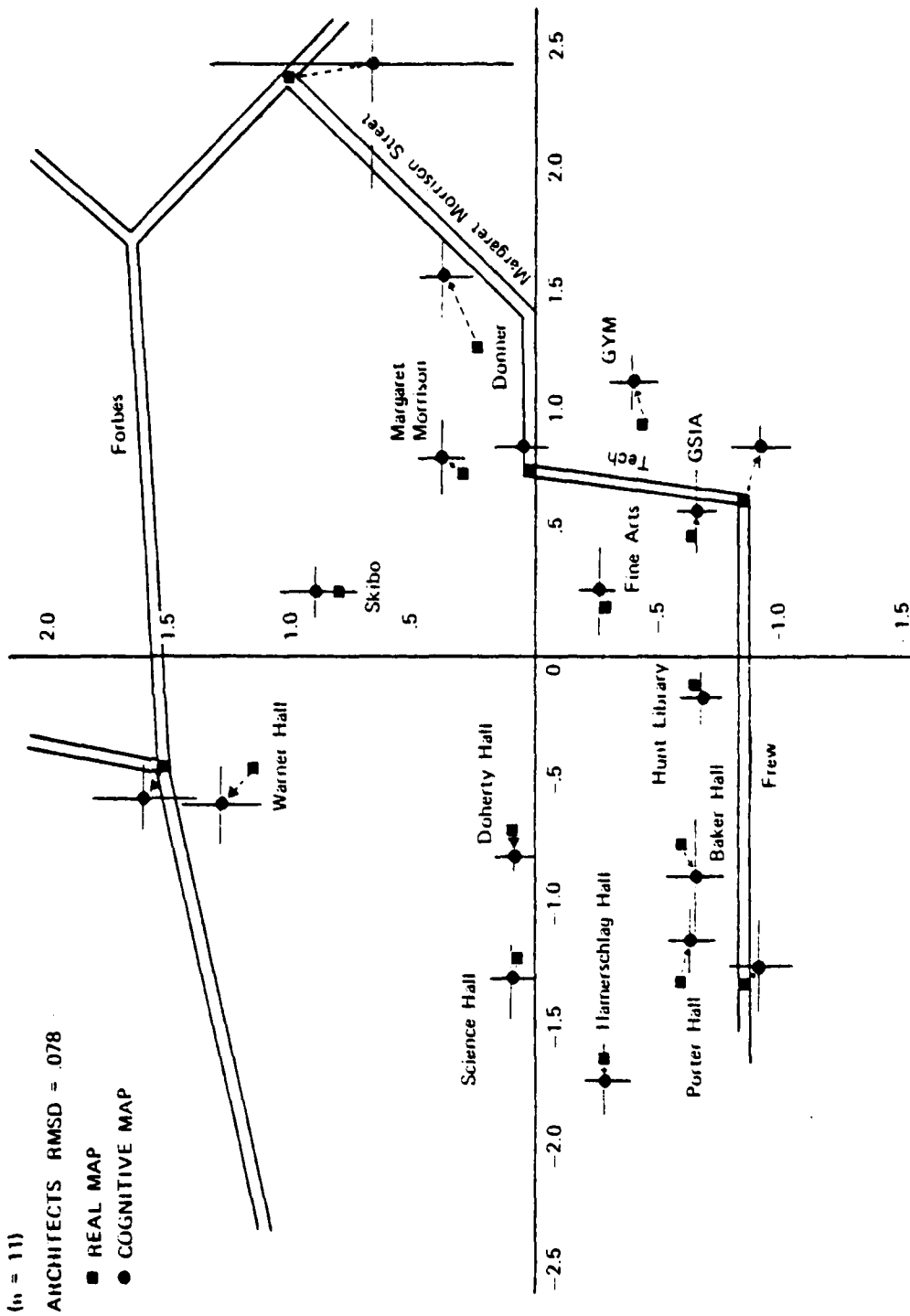


Figure 1. Architects' (11) average map of the Carnegie Mellon University Campus for 18 well known campus buildings and street intersections. Squares indicate reported locations, bracketed by ± 1 standard deviation between subjects in the x and y dimensions. Dashed lines indicate the discrepancy between the actual and reported locations, the standard deviation of these errors (RMSD) is shown in the upper left. Streets bordering the campus are also shown. Before averaging, each subject's map was standardized in the x and y dimensions, and the map scale is in terms of the z scores.

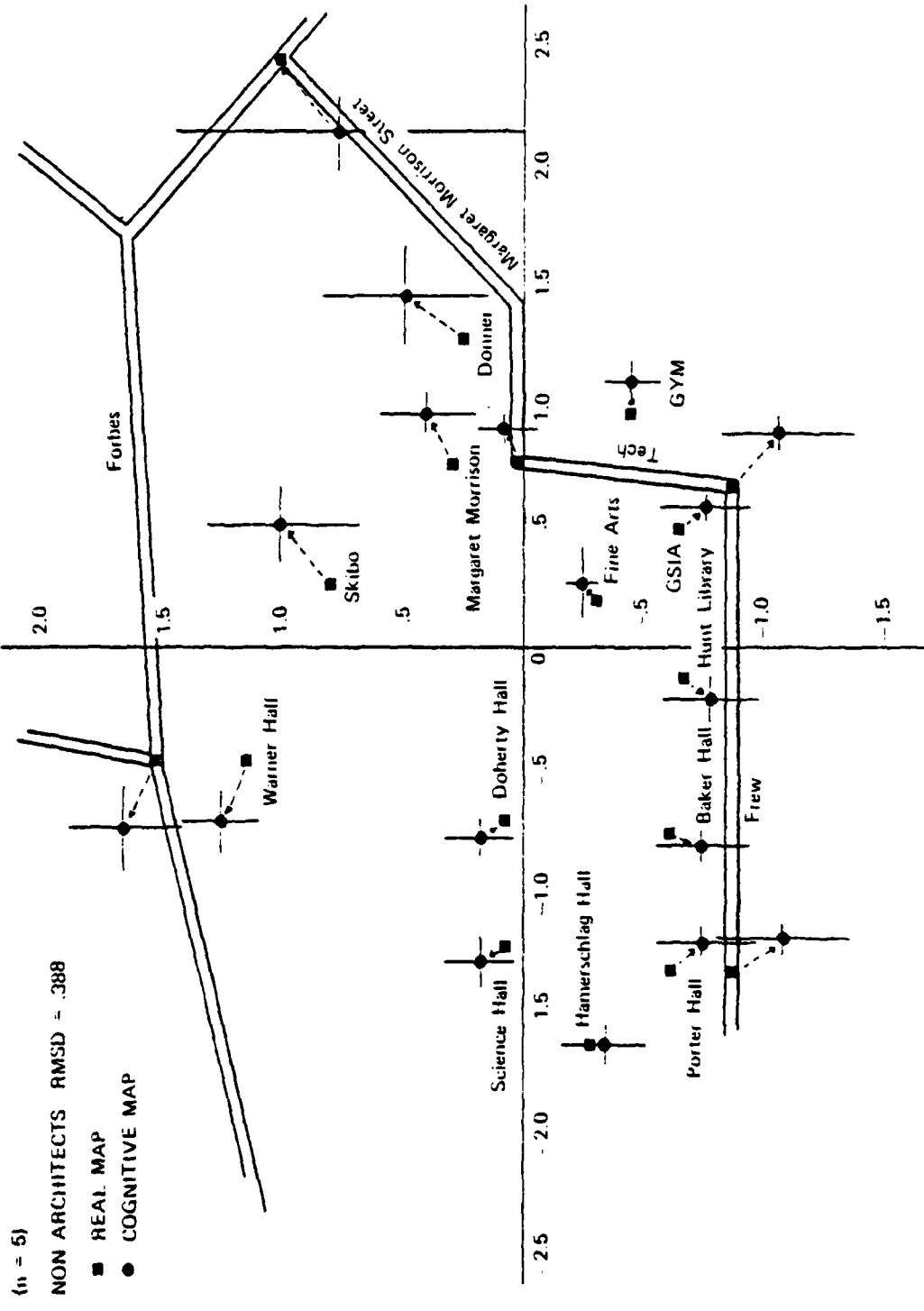


Figure 2. Nonarchitects' (5) map of the CMU Campus.

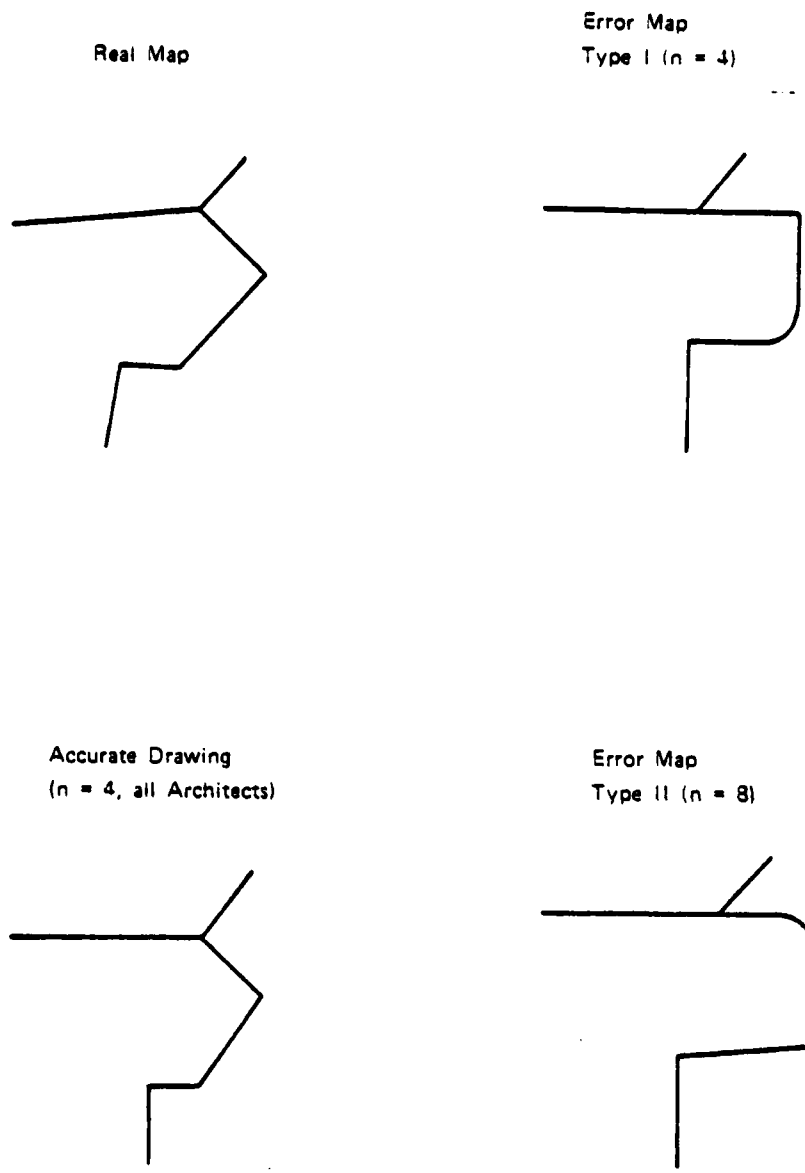


Figure 3. Average maps for the only streets bordering the CMU campus, for three different types of subjects, depending upon how they reported the one intersection at 45° with respect to the rest of the environment. The real map (upper left) is compared to the three types of subjects: (1) Those who drew the intersection correctly (lower left, all architects), (2) those who forced Margaret Morrison Street to take a right-angle turn (upper right), and (3) those who forced Forbes Avenue to take a right-angle turn (lower right).

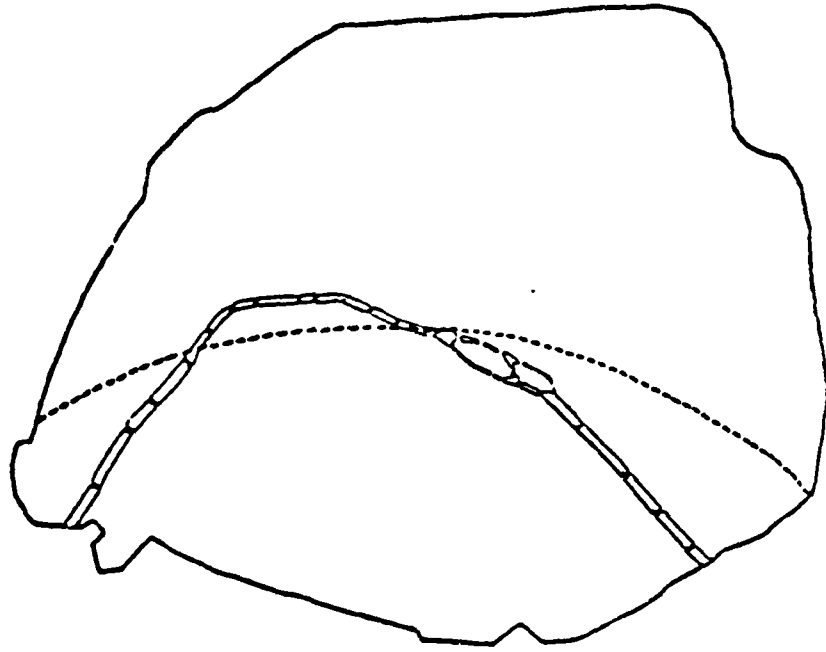


Figure 4. A comparison of the reported curvature of the Seine River (dotted line) and the actual course of the river through Paris. The dotted line represents the median curvature, based on 218 Parisians. From Milgram and Jodelet (1976). Reprinted by permission.

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