COGNITIVE PSYCHOLOGY **18**, 87–121 (1986)

Mental Representations of Spatial Relations

TIMOTHY P. MCNAMARA

Vanderbilt University

Three classes of theories of the mental representation of spatial relations were tested. *Nonhierarchical theories* propose that spatial relations among objects in an environment are mentally represented in networks or in imagelike, analog formats. The distinctive claim of these theories is that there is no hierarchical structure to the mental representation. *Hierarchical theories*, on the other hand, propose that different "regions" of an environment are stored in different branches of a graph-theoretic tree. These theories can be divided into two classes of subtheories depending on the kinds of relations encoded in memory: *Strongly hierarchical theories* maximize storage efficiency by encoding only those spatial relations needed to represent a layout accurately; *partially hierarchical theories* predict redundancy in the representation, such that many spatial relations that can be computed also will be stored explicitly. These three classes of theories were tested by having subjects learn the locations of actual objects in spatial layouts or the locations of objects on maps of those layouts. Layouts and maps were divided into regions with transparent boundaries (for the layouts, string on the floor; for the maps, lines). After learning the layouts or maps, subjects participated in three tasks: item recognition, in which the variable of interest was spatial priming; direction judgments; and euclidean distance estimation. Results from all three tasks were sensitive (a) to whether objects were in the same region or in different regions and (b) to the euclidean distances between pairs of objects. These findings were interpreted as supporting partially hierarchical theories of spatial representations. Computer simulations supported this conclusion.

Nearly all human activities require that we represent spatial relations. We navigate in three-dimensional environments, guided by our perception of and memory for spatial relations. We describe the process of thinking as though it extended in space (e.g., we compare "linear" to "nonlinear" thinking). Objects of our thoughts, such as mental images, seem to have

This research was supported in part by an award from the Vanderbilt University Research Council and by NSF Grant BNS-8417741. Parts of this article were included in a dissertation submitted to Yale University in partial fulfillment of the degree of Doctor of Philosophy. I am grateful to Robert J. Sternberg, Robert P. Abelson, Wendell R. Garner, Roger Ratcliff, and Arthur Samuel for their trenchant comments during early stages of the research and on an earlier version of this manuscript. I also thank P. N. Johnson-Laird and two anonymous reviewers for their helpful comments on earlier drafts. Requests for reprints should be sent to Timothy P. McNamara, Department of Psychology, Vanderbilt University, 134 Wesley Hall, Nashville, TN 37240.

0010-0285/86 $7.50

spatial properties. And our language is imbued with spatial metaphors. Shepard (1975, 1981, 1984) has argued that physical contraints unique to our spatial environment have been internalized, via evolution, in our perceptual system; and he has suggested that these constraints might be embodied in the structure and mental processing of language. Understanding how spatial knowledge is acquired, stored and organized in memory, and used in everyday activities would seem to be fundamental for any theory of complex mental functioning.

The research reported in this article focused on a specific problem in spatial cognition; viz., how spatial relations among objects in an environment are encoded in memory. The principal goals of this research were to test alternative theories of the mental representation of spatial relations and to assess whether or not these theories applied equally well to knowledge acquired from maps and knowledge acquired from direct experience.

THEORIES OF SPATIAL REPRESENTATIONS

Theories of mental representations, in general, and theories of spatial representations, in particular, can be distinguished in at least four ways. One characteristic is the proposed *form,* or type of mental code used to represent knowledge in memory. For example, spatial information might be mentally represented in an analog format (e.g., Kosslyn, 1975; Kosslyn & Pomerantz, 1977; Paivio, 1975; Shepard, 1975), in an abstract propositional format (Pylyshyn, 1973; Stevens & Coupe, 1978), or in a hybrid analog–propositional format (Anderson, 1978, 1983; Kosslyn & Shwartz, 1977). A second distinguishing characteristic is the *function* of the representation (Anderson, 1983; Johnson-Laird, 1983). For example, analog representations are quite useful for encoding spatial configurations of objects but less useful for encoding semantic or logical knowledge. Propositional representations, on the other hand, are quite useful for encoding semantic or logical knowledge but less useful for encoding spatial configurations (Anderson, 1983). A third characteristic is the proposed *structure,* or kinds of relations allowed among codes. For example, the "nonhierarchical" structure of an analog representation or of a network of abstract propositions could be contrasted with a "hierarchical" representation, in which increasingly more detailed information was stored at lower and lower levels of the hierarchy (e.g., Stevens & Coupe, 1978). Finally, theories of mental representations can be distinguished on the basis of their *contents*. For example, two theories of spatial representations might be distinguished because one proposes that distances between certain objects are computed whereas the other theory proposes that these same distances are encoded in the representation. This distinction is similar to one made by Smith (1978) between theories of semantic memory: In certain theories, category relations are computed (e.g., Smith, Shoben, & Rips, 1974), whereas in other theories, these relations are "prestored" (e.g., Glass & Holyoak, 1975).

The research described here focuses on the latter two characteristics, the structure and contents of spatial representations. In this section of the article, three classes of theories of the mental representation of spatial relations are considered. These theories are distinguished on the basis of the proposed structure of the representation. This classification is only one of many ways that theories of spatial representations might be distinguished, and ultimately, might prove to be oversimplified. Nevertheless, it does capture many important and empirically testable differences among existing theories of spatial representations.[1]

Nonhierarchical Theories

According to nonhierarchical theories, spatial relations among objects are mentally represented in propositional networks (Byrne, 1979), in analog representations with continuously varying properties (Kosslyn, Ball, & Reiser, 1978; Levine, Jankovic, & Palij, 1982; Thorndyke, 1981), or (possibly) both. The important claim of these theories is that there is no hierarchical structure to the representation; everything is represented at the "same level." Again, whether the representation is propositional, imaginal, or both is not important for current purposes, although resolving this fundamental representational issue may be an important problem in general for research on spatial cognition.

An example of these theories has been proposed by Byrne (1979). According to Byrne, memory for an urban environment can be viewed as a network that preserves topological connectedness (the order of locations and turns) but not two-dimensional orientation and distance information (as a map would). Locations in a layout correspond to nodes in the network and paths between locations correspond to links between the nodes. Byrne argues that this theory is supported by findings that (a) estimates of urban distances increase with increasing numbers of turns (controlling for actual distance) and with increasing familiarity; and (b) that estimates of angles between urban roads tend to be distorted towards 90°, regardless of the actual angle (Byrne, 1979). The first class of results can be explained by assuming that subjects rely on the simple heuristic that the

[1] A class of theories that is conspicuously absent from the forthcoming trichotomy comprises those theories distinguishing "procedural knowledge" from "survey knowledge" (e.g., Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982). This distinction is an important and useful one, but it does not require claims (explicit or implicit) about the mental representation of spatial knowledge. Indeed, extant discussions of these theories have not made such claims. The distinction between procedural and survey knowledge cuts across the structural distinctions proposed here.

more locations remembered on a route, the longer the route must be. Presumably, routes with numerous turns will have more locations encoded than routes with few turns, and familiar routes will have more locations encoded than unfamiliar routes. The second class of results is easily explained if angular information is not encoded in spatial representations.

Hierarchical Theories

According to hierarchical theories, different "regions" of an environment are stored in different branches of a graph-theoretic tree. The mental representation is organized such that increasingly more detailed spatial knowledge is given at lower and lower levels of the hierarchy. Regions might be defined by physical boundaries (e.g., walls between rooms); perceptual boundaries (e.g., lines on a map); or even subjective boundaries that individuals impose on undifferentiated spatial environments (see, e.g., Hirtle & Jonides, 1985). Hierarchical theories can be divided into two classes of subtheories depending on the kinds of spatial relations encoded in memory.

Strongly hierarchical theories. These theories propose that spatial relations are not encoded between locations in different branches of the hierarchy; these spatial relations must be inferred from higher order spatial knowledge. For example, under these theories, the spatial relations between two cities in the same state would not be stored in memory, but would be inferred from knowledge of the relative positions of the cities within the state. This class of theories represents an extreme position in the trade-off between storage and computation.

Partially hierarchical theories. Partially hierarchical theories, unlike strongly hierarchical theories, allow spatial relations to be encoded between locations in different regions of an environment. These theories are less efficient than strongly hierarchical theories in terms of the storage of spatial knowledge, since spatial relations that could be inferred also might be explicitly encoded. The principal advantage of this redundancy would be the increased speed and accuracy with which certain spatial judgments could be performed. (This advantage follows from the assumption that, at least in many cases, knowledge encoded in memory could be retrieved faster and more accurately than the same knowledge could be inferred from other knowledge in memory.) Partially hierarchical theories, in various guises, have been proposed by Davis (1981) and McDermott (1981), by Kuipers (1978), and by Stevens and Coupe (1978).

An example of the usefulness of hierarchical theories (both strongly and partially hierarchical) stems from an analysis of the errors that people often make when judging spatial relations. For example, most of us do not have the spatial relation between Reno, Nevada, and San Diego,

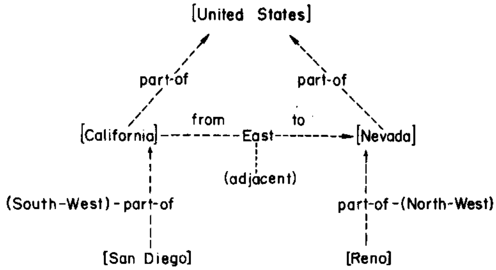

FIG. 1. A possible hierarchical representation of the spatial relations among San Diego, Reno, California, and Nevada. Regions are identified as names in square brackets; spatial relations between regions are identified as labeled links.

California encoded in our cognitive map of the continental United States.[2] If asked, we would probably say that Reno was east of San Diego, based on our knowledge that Nevada is east of California. We might even be so bold as to say that Reno was northeast of San Diego, if we knew that Reno and San Diego were in the northern and southern parts of their respective states. In fact, Reno is northwest of San Diego. According to the theory advanced by Stevens and Coupe (1978), spatial judgments such as this one are distorted because spatial information is stored as in Fig. 1. This figure contains a schematic representation of the spatial relations between locations in California and Nevada. The notation in the figure is loosely based on the notation used by Stevens and Coupe (1978): Regions are identified as names in square brackets; spatial relations between regions are identified as labeled links. An important aspect of this representation is that spatial relations between cities in different states are not explicitly represented. (The spatial relations between states, however, are explicitly represented. Hence, this representation is partially hierarchical not strongly hierarchical. If the link between California and Nevada were removed, this representation would be strongly hierarchical.) To judge the spatial relation between San Diego and Reno, three sources of information must be combined: (a) the spatial relation between San Diego and California; (b) the spatial relation between California and Nevada; and (c) the spatial relation between Nevada and Reno. Distortions in judged spatial relations could arise because superordinate spatial relations were weighted heavily by inference processes; because the spatial relations between locations (e.g., San Diego) and superordinate regions (e.g., California) were stored inaccurately; or both. For example, if we assume that the locations of San Diego and Reno were encoded accurately, then distortions might be caused by heavily weighting the knowledge that Ne-

[2] The term "cognitive map" refers to the mental representation of spatial knowledge. It does not imply that the representation is "maplike." This usage corresponds to the term's meaning when it was coined by Tolman (1948).

vada is east of California: Nevada is east of California, therefore Reno must be east of San Diego. Stevens and Coupe (1978) have shown that distortions like this one occur for several geographical locations (e.g., the Atlantic entrance of the Panama Canal is northwest of the Pacific entrance; New York is west of Santiago, Chile), as well as for artificial stimuli.

Although distortions in judged spatial relations have been used to support hierarchical theories (Stevens & Coupe, 1978), these data do not rule out nonhierarchical theories. A nonhierarchical theory would explain distortions by assuming that the mental representation was distorted. This problem is an example of a methodological issue of concern among researchers in the area of spatial cognition: the relative abilities of various tasks to inform us about the structure and contents of spatial representations.

METHODS FOR STUDYING SPATIAL KNOWLEDGE

Many tasks have been used to study spatial representations and processes. Some of the more common ones have been *distance estimation* (e.g., Cohen & Weatherford, 1980; Baird, Merrill, & Tannenbaum, 1979; Kosslyn, Pick, & Farriello, 1974; McNamara, Ratcliff, & McKoon, 1984; Newcombe & Liben, 1982; Rieser, Lockman, & Pick, 1980; Thorndyke, 1981; Thorndyke & Hayes-Roth, 1982); *orientation judgments* (e.g., Hardwick, McIntyre, & Pick, 1976; Hintzman, O'Dell, & Arndt, 1981; Kozlowksi & Bryant, 1977; Presson & Hazelrigg, 1984); *map drawing* (e.g., Appleyard, 1970; Baird et al., 1979; Lynch, 1960; Piaget, Inhelder, & Szeminska, 1960; Tversky, 1981); and *navigation* (e.g., Acredolo, Pick, & Olsen, 1975; Anooshian & Young, 1981). All of these tasks are informative about certain aspects of spatial cognition and spatial behavior. However, there are reasons to question the extent to which these tasks are informative about the structure and contents of spatial representations (Downs, 1981; Liben, 1981, 1982; Newcombe, 1981; Siegel, 1981). The focus of these criticisms has been on the extent to which patterns of performance in a particular task are produced by the structure and contents of the mental representation or by retrieval and inference processes acting on the representation. Siegel (1981) has suggested that experiments testing spatial representations should employ tasks that minimize performance demands so that properties of the mental representation could be assessed more accurately. A task that might meet this requirement is *priming in spatial memory*. McNamara et al. (1984) used priming in recognition to examine the mental representation of knowledge acquired from maps. (See Clayton & Chattin, 1981, for another spatial priming task.) McNamara et al. had subjects learn the locations of cities on simple road maps. After learning each map, subjects participated in a recognition

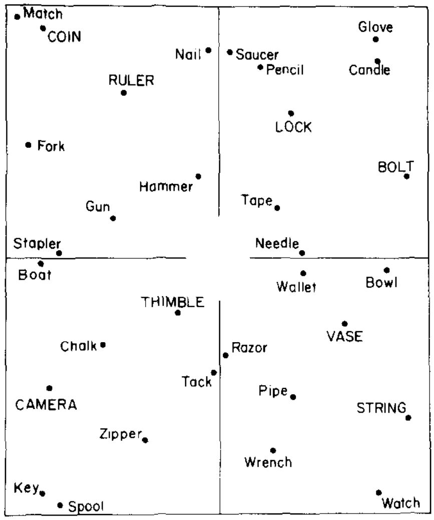

FIG. 2. An example of one of the spatial layouts used in the experiment.

test for cities on the map. The dependent measure was the extent to which subjects recognized a target city faster if, on the immediately previous trial, they had just recognized a city close to the target on the map. In other words, the variable of interest was priming between sequential items in the recognition test as a function of distance on the map. McNamara et al. found that subjects recognized a target city faster when it was primed by a city close to the target in route distance than when it was primed by a city far from the target in route distance (even when euclidean distance was equated). These results suggested that priming in recognition could be used to assess the relative psychological distances between locations in spatial memory.

An advantage of priming over many other tasks is that priming is probably not influenced by retrieval strategies. Ratcliff and McKoon (1981a) have shown that recognition priming in memory for sentences is insensitive to the probability of a priming event and has a very fast onset (about 50 ms). These qualities indicate that priming is primarily an automatic process (as defined by Posner & Snyder, 1975a, 1975b). Because priming is primarily automatic, it should be informative about the kinds of knowledge encoded in memory and how that knowledge is organized.

The theories were tested by having three groups of subjects learn the locations of objects in spatial layouts. These layouts were divided into four regions, as in Fig. 2. (Ignore, for the moment, object names typed in capital letters.) Subjects in the map group learned maps of spatial layouts (Fig. 2 is an example of such a map); subjects in two direct-experience groups learned the locations of actual objects in spatial layouts. The maps and layouts were divided into regions with transparent boundaries in an attempt to induce subjects to encode spatial relations hierarchically.

Two direct-experience groups were employed in order to assess the effects of "functional" distance on the organization of spatial knowledge (Pick & Lockman, 1981). These two groups were distinguished on the basis of how subjects were allowed to navigate in the spatial layouts: Subjects in the free-navigation group were allowed to walk freely across the region boundaries when learning the locations of objects, whereas subjects in the constrained-navigation group were prohibited from crossing the region boundaries. For subjects in the free-navigation group, functional distance was equal to euclidean distance, since the path from one location to another was unobstructed. In contrast, for subjects in the constrained-navigation group, functional distance between locations in different regions was greater than euclidean distance: To walk from a location in one region to a location in another region, subjects had to walk around a region boundary. The effects of transparent vs opaque boundaries (e.g., walls) have been examined in other studies (e.g., Kosslyn et al., 1974; Newcombe & Liben, 1982), but to my knowledge transparent boundaries that obstruct navigation have never been compared to transparent boundaries that do not obstruct navigation. This comparison is necessary because it tests the effects of functional distance on the organization of spatial knowledge when visual distance is held constant.

The locations of objects in spatial layouts were varied in order to test attributes of subjects' mental representations. The distance between objects (close vs far) was crossed with whether objects were in the same region or in different regions. (For examples of objects in these conditions, consult the Method section.) Furthermore, objects in different regions (but only objects in different regions) could be "aligned" or "misaligned" with respect to their regions. In Fig. 2, for example, the needle and the wallet have a vertical orientation, which is aligned with the vertical orientation of their respective regions. In contrast, the stapler and the boat have a diagonal orientation, which is misaligned with the vertical orientation of their respective regions. Alignment also was manipulated between far objects (contrast the zipper and wrench with the hammer and pencil). This manipulation was included in order to examine distortions in judged spatial relations as a function of superordinate spatial relations.

After subjects learned a spatial layout, they participated in three tasks: recognition of object names (the spatial priming task), judgments of the directions of objects relative to other objects, and euclidean distance estimation. Subjects also received tests of verbal and spatial ability. The various patterns of results from the three groups and three tasks that

TABLE 1
Major Predictions of the Theories for Priming

	Nonhierarchical	Strongly hierarchical	Partially hierarchical
Overall effect of region membership	No	Yes	Yes
Distance effect across region boundaries	Yes	No	Yes

Note. Strongly hierarchical theories and the theory proposed by Stevens and Coupe (1978) predict the same results.

might distinguish the theories are too numerous to outline step by step. But with a few reasonable assumptions about priming in recognition, all three of these theories predict patterns of performance in the priming task.

The first assumption is that priming in recognition is caused by an automatic retrieval process, which can be characterized as activation "spreading" through memory. This assumption receives strong support from recent work on memory for text (Ratcliff & McKoon, 1981a). The second assumption is that the amount of activation arriving at a memory trace is inversely related to its distance (in memory) from a source of activation (such as the memory trace corresponding to a priming stimulus). In other words, priming can be used as a measure of psychological distance in memory. This assumption has been supported by several lines of research, including investigations of memory for facts (e.g., Anderson, 1976, 1983) and memory for text (Ratcliff & McKoon, 1981b). The third, and final, assumption is that the time required to retrieve a concept from memory is inversely related to the activation level of that concept. That is, recognition times decrease as activation levels increase. This assumption has been supported by findings that asymptotic activation levels, not times for activation to spread, are the critical determinants of retrieval times (Ratcliff & McKoon, 1981b; Schustack, 1981).

Given these assumptions, we can examine several predictions of these theories for priming. Table 1 contains a summary of the major predictions of each class of theories.

Nonhierarchical theories would be supported if close objects (in the spatial layouts) primed each other more than far objects, but region boundaries did not affect priming. These theories would not be ruled out by effects of boundaries on priming, but such results, in particular, certain patterns of boundary effects, might be difficult for nonhierarchical theories to predict a priori. For example, these theories would have difficulty with the possible result that distance has no effect on priming across region boundaries. This result would indicate that subjects were not encoding the spatial relations between objects in different regions even when those objects were only 1 ft apart.

Strongly hierarchical theories and the partially hierarchical theory proposed by Stevens and Coupe (1978) predict similar patterns of results. To the extent that subjects' mental representations reflect the hierarchical structure of the layouts, these theories predict (a) that locations in the same region should prime each other more than locations in different regions, but (b) no effects of distances on priming across region boundaries. The first prediction follows from the hierarchical structure of the representation, in which locations in the same region would tend to be encoded in the same branch of the hierarchy. This encoding scheme creates an additional component to psychological distance; viz., whether locations are in the same branch or in different branches. The second prediction follows from the claim that spatial relations between objects in different regions are not represented in memory. For strongly hierarchical theories, these interconnections never occur in the mental representation; for the partially hierarchical theory proposed by Stevens and Coupe (1978), these interconnections do not occcur between locations with different superordinates (in this experiment, objects in different regions). In both cases, distances between objects in different regions are not encoded in memory, and consequently, there should be no effects of these distances on priming in recognition. This prediction may seem unreasonably strong. Yet Stevens and Coupe (1978) argued that distortions in judged spatial relations were caused because spatial relations were not encoded across region boundaries. Their stimuli contained perceptual boundaries very similar to the ones used here.

Partially hierarchical theories (in which spatial relations are encoded across region boundaries) predict two major results. First, these theories, like strongly hierarchical theories (and for the same reason), predict that objects in the same region of a spatial layout should prime each other more than objects in different regions. Second, these theories, like nonhierarchical theories, predict a priming effect across region boundaries. The latter prediction distinguishes partially hierarchical from strongly hierarchical theories.

METHOD

Subjects

The subjects were 72 Yale University students, 24 in each of three groups. Subjects were randomly assigned to groups. Half the subjects in each group were female. Subjects were compensated for their participation with course credit, monetary payment, or both.

Experimental Space

The experimental space for the direct-experience groups was a 20 × 24-ft area delineated within a 28 × 30-ft room. The space was divided into four regions with transparent boundaries (string attached to the floor) and contained a 3 × 4-ft open area in the center.

Design

Independent variables. The independent variable corresponding to learning group (map, free navigation, and constrained navigation) was between subjects. The remaining three independent variables were within subjects and determined the spatial relations between pairs of object locations: *Distance* determined whether two locations were close together or far apart; *region* determined whether two locations were in the same region or in different regions; and *alignment* determined whether two locations in different regions were aligned or misaligned with respect to their regions. These three within-subjects variables were combined to form six conditions: (a) close together and in the same region (e.g., key and spool in Fig. 2); (b) far apart and in the same region (e.g., match and fork); (c) close together, in different regions, and aligned with the regions (e.g., needle and wallet); (d) close together, in different regions, and misaligned with the regions (e.g., stapler and boat); (e) far apart, in different regions, and aligned with the regions (e.g., zipper and wrench); and (f) far apart, in different regions, and misaligned with the regions (e.g., hammer and pencil). The design was incomplete in that alignment was manipulated between regions but not within regions.

Dependent variables. The dependent variables were response accuracy and latency in the recognition task; response accuracy and confidence ratings in the direction judgment task; and response accuracy in the distance estimation task.

Materials

The layouts. Subjects learned two spatial layouts. Subjects in the direct-experience groups learned the locations of actual objects in these layouts; subjects in the map group learned maps of these layouts.

Each layout contained 32 locations, 8 in each of four regions. These 32 locations could be divided into 12 pairs of locations in the six experimental conditions (two per condition) and 8 "filler" locations (2 per region). Subjects were required to learn the locations of objects on the 24 experimental locations, but not the 8 objects on the filler locations. (The recognition test required that some objects in a layout not occur in any of the experimental conditions. It was originally thought that subjects would have great difficulty learning the locations of 24 objects, let alone 32. Consequently, subjects were required to learn only the locations of the 24 objects on the experimental locations.) For the direct-experience groups, locations were marked with disks of construction paper 4 in. in diameter. The experimental locations were marked with white disks and the fillers were marked with red disks. On the maps, locations were marked with black dots (as in Fig. 2). Filler locations were marked by typing the names of the objects on these locations in capital letters (e.g., CAMERA in Fig. 2).

Close locations in the experimental space were 1 ft apart; far locations were 6 ft apart. The angular deviations between the orientations of aligned locations and their superordinate regions ranged from 0 to 5°. The angular deviations between the orientations of misaligned locations and their superordinate regions ranged from 54 to 60°. As an example, consider Fig. 3. In the lower half of this figure, a solid line connects two locations that are far apart, in different regions, and *aligned* with respect to their regions. A dashed line indicates the spatial relation between the two regions. The angle between the solid and dashed lines is 5°. As a second example, consider the upper half of Fig. 3. There, a solid line connects two locations that are far apart, in different regions, and *misaligned* with respect to their

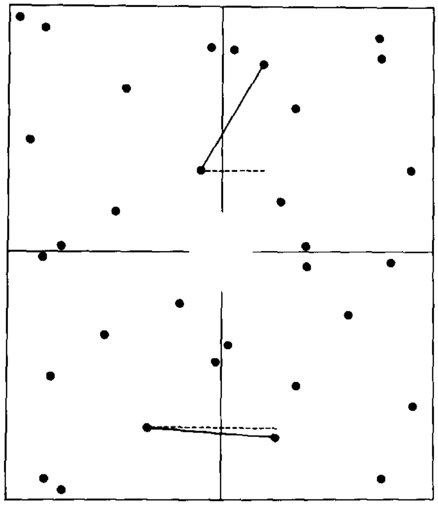

FIG. 3. A diagram of the variable manipulated in the alignment condition. Dashed lines are the spatial relations between regions. Solid lines are the spatial relations between objects. The angles between dashed and solid lines ranged from 0 to 5° for aligned objects (lower half of figure), and ranged from 54 to 60° for misaligned objects (upper half of figure).

regions. As before, a dashed line indicates the spatial relation between the regions, but the angle between the solid and dashed lines is 60°. Subjects in the map group learned maps of the two spatial layouts. Maps occupied most of the area on 8.5 × 11-in. sheets of paper and were drawn to the scale of 1 in.:2.5 ft.

Six versions of each layout (and six corresponding maps) were constructed by rotating each pair of objects through all six experimental conditions. The locations of objects on the filler locations did not vary across versions of a layout. Versions of a given layout were assigned to subjects according to a fixed rotation determined by the order in which subjects participated in the experiment.

Objects were selected by first constructing a list of 96 object names. Names on the list were names of portable, common objects or names of objects that could be presented as toys (e.g., boat and truck). Stimulus pairs (i.e., pairs of objects in the experimental conditions) were constructed by pairing 24 of these names with another 24 names. Pairs were constructed so that there were no discernible semantic or functional relationships between the objects in a pair. Half of these pairs were randomly assigned to one of the layouts and the other half were assigned to the other layout. Sixteen object names were selected from the remaining 48 names and randomly assigned to the filler locations on the two layouts, 8 names per layout. Finally, the remaining 32 names in the pool were used as foils in the recognition tests. After dividing the names in this manner, a collection of 64 actual objects (48 objects in the experimental conditions and 16 fillers) was assembled. These objects were then placed on the appropriate locations for the direct-experience groups. A list of the names of the objects appearing as stimulus pairs and those appearing as foils can be found in the Appendix.

Recognition. Materials were two lists (one per layout) of 48 object names. Twenty-four of these names were prime-target pairs. Eight of the 48 names on a list were names of objects on filler locations. The remaining 16 names were foils, i.e., names of objects that did not appear in either layout. Recognition lists were constructed so that (a) an object name appeared only once on a list, and (b) targets appeared no earlier than the fourth position on a list. All subjects in the experiment saw the same recognition lists.

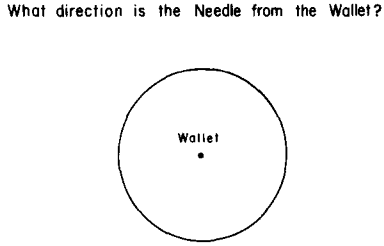

FIG. 4. An item used in the direction judgment task. Subjects indicated the direction of a target object (needle) from an anchor object (wallet) by drawing a line from the center of the circle to the periphery.

Direction judgments. Materials were two lists (one per layout) of 12 items similar to the one illustrated in Fig. 4. The task was to indicate the direction of a target object (needle in Fig. 4) from an anchor object (wallet in Fig. 4) by drawing a line from the center of the circle to the periphery. The order of items on each list was random and the same for all subjects.

Distance estimation. Materials were two lists (one per layout) of 24 pairs of object names. Half the items were experimental pairs, and half were fillers obtained by re-pairing the experimental pairs. Each object name appeared once as the right member of a pair and once as the left member. The order of items was random and the same for all subjects.

Although the stimuli for the three tasks were the same for all subjects, the objects actually occurred in different experimental conditions across subjects. This is because subjects learned different versions of the layouts. Across groups of 6 subjects, each pair of objects appeared in each experimental condition. Thus, within each experimental group (24 subjects), each pair of objects appeared in each condition four times.

Reference ability tests. Subjects were given the Verbal Reasoning section of the Differential Aptitudes Test (DAT) (Bennett, Seashore, & Wesman, 1974) and the Vandenberg (1971) test of three-dimensional spatial visualization.

Procedure

Subjects learned a layout (or map of a layout) and then participated in a recognition test, direction judgment test, and distance estimation test. This sequence—space learning, recognition, direction judgments, and distance estimations—was performed for each layout. The order in which subjects learned the layouts was counterbalanced within groups.

Direct-experience groups. Subjects in these groups learned the locations of actual objects in the experimental space. Subjects were asked to learn the names and locations of objects on white disks (the experimental locations), but only the names of objects on red disks (the filler locations). (See the Materials section for the reasoning behind this request.) Subjects in the free-navigation group were allowed to walk freely through the space when learning the locations of objects. Subjects in the constrained-navigation group were prohibited from crossing the region boundaries: To cross the room, subjects had to walk around the boundaries as though the boundaries were walls. Subjects in both groups were given 2 min to study the locations of the objects. After the study period, all of the objects on experimental locations (but not the objects on filler locations) were removed from their locations and placed in a box in the center of the room. Subjects then attempted to place all of the objects on their correct locations. Subjects named the objects aloud the first time they placed the objects in order to ensure that they were using the same names that were used in the experimental materials. The study–test procedure was repeated until subjects could place the objects correctly twice (but not necessarily twice in a row).

Map group. Subjects in this group learned maps of the layouts. Subjects were told that they should learn the names of objects typed in capital letters (filler locations) but not the locations of these objects. Subjects were given 2 min to study a map. Subjects then were given a list of the nonfiller object names and a test map. Test maps contained the locations of objects (indicated by dots), the names of filler objects typed in capital letters, but not the names of objects on experimental locations. The subjects' task was to place all of the object names on their correct locations. This study–test procedure was repeated until subjects could place the object names correctly twice. After learning a layout or map, subjects in all groups participated in three tasks:

First, subjects were given a recognition test. Object names were displayed one at a time on a computer terminal screen. The subjects' task was to decide whether or not the named object was in the space or on the map just studied. Two hundred fifty milliseconds elapsed between a response and the presentation of the next object name. This response–stimulus interval was chosen to minimize strategic processing between trials (Neely, 1977; Posner & Snyder, 1975a, 1975b; Ratcliff & McKoon, 1981a).

Second, subjects were given the direction judgment test. In this test, subjects judged the directions of objects in the layouts relative to other objects. For each item (see Fig. 4), subjects were asked to imagine standing at the object in the center of the circle (the wallet in Fig. 4), facing in a particular direction. The orientation was the same for all items and all subjects. Subjects were asked to draw a line from the center of the circle to its periphery indicating the direction of the "target" object (the needle in Fig. 4). After completing each direction judgment, subjects rated their confidence on a 1–9 scale, where a rating of 1 meant *not at all confident* and a rating of 9 meant *very confident*.

Third, and finally, subjects participated in a distance estimation test. Subjects were shown pairs of objects on a terminal screen and asked to estimate the euclidean distance in feet between the objects. Subjects in the map group were told that a distance of 1 in. on the map corresponded to 2.5 ft. Subjects in all three groups were given the distance between two filler locations as an example.

In a second session, subjects were given the reference ability tests. Subjects were allotted 15 min for the DAT and 10 min for the Vandenberg.

RESULTS

Preliminary analyses were conducted on the data from each of the tasks to examine the effects of layouts, learning order, and the serial position in which a given layout was learned. These variables did not, in general, interact with any of the experimental effects (region, distance, and alignment). There were, however, significant effects involving layouts, learning order, and serial position, in the distance estimation data. These interactions were produced because the sizes, but not the directions, of certain effects varied across the variables of layouts, order, and serial position. Distance estimations were collapsed across these variables in subsequent analyses.

Recognition

Analyses were performed on the mean correct response latencies for the targets in each condition. Only correct responses preceded by correct responses were included in the analyses to ensure that both prime and target were in memory at time of test. In addition, all latencies that ex-

TABLE 2
Mean Response Latencies and Error Rates in the Recognition Task

	Same region		Different regions	
	Close	Far	Close	Far
Map				
RL	686	727	718	736
Errors	0.0	2.1	2.0	3.6
Free navigation				
RL	713	789	776	802
Errors	4.2	4.2	2.6	4.7
Constrained navigation				
RL	717	788	794	831
Errors	4.2	1.0	3.1	1.6
Overall				
RL	705	768	763	790
Errors	2.8	2.4	2.6	3.3

Note. Latencies are in milliseconds; errors are percentages. RL = response latencies.

ceeded the outer, upper fence (Tukey, 1977) for each group and each condition were excluded from analyses of response latencies.[3] Out of 1635 responses meeting the first condition (correct responses preceded by correct responses) 50 were classified as outliers. Outliers were evenly distributed across subjects and conditions. Error rates for targets were quite low: The overall error rate was 2.8 ± 0.4%. Because there were no significant effects on error rates of any of the experimental conditions, these analyses are not reported.

A preliminary analysis showed that alignment had no effects on latencies nor did it interact with any other variable.[4] Consequently, response latencies were collapsed across this variable in subsequent analyses. The mean trimmed correct response latencies, collapsed across alignment, are presented in Table 2. This table also contains average error rates.

Subjects recognized a target object 40 ms faster, on the average, when it was primed by an object in the same region than when it was primed by an object in a different region, $F(1,69) = 15.06$, $p < .001$. Subjects also recognized a target object 45 ms faster, on the average, when it was primed by a close vs a far object, $F(1,69) = 13.22$ $p < .001$. Both of these effects were statistically reliable when materials were treated as the

[3] The outer, upper fence is equal to the 75th percentile + [3 × (75th percentile − 25th percentile)].

[4] The only significant effect in this analysis was that of distance across region boundaries. This 27-ms effect was statistically reliable across subjects, $F(1, 69) = 5.55$, $p < .025$, and across materials, $F(1, 23) = 5.67$, $p < .05$.

random effect: $F(1,23) = 15.94$, $p < .001$, for the effect of region; and $F(1,23) = 19.84$, $p < .001$, for the effect of distance. The size of the distance effect was larger when the prime and target were in the same region (mean difference of 63 ms) than when the prime and target were in different regions (mean difference of 27 ms), $F(1,69) = 3.91$, $p = .052$. A critical comparison for testing strongly hierarchical theories was to examine the distance effect across region boundaries. A planned comparison showed that this 27-ms effect was statistically reliable, $F(1,69) = 4.03$, $p < .05$. (See Footnote 4 also.) There were no other significant effects in the analysis of response latencies.

The mean correct response latency and mean error rate for primes were 858 ± 8.6 ms and 2.8 ± 0.4%; means for fillers were 1001 ± 16.2 ms and 16.6 ± 1.1%; and means for foils were 1013 ± 11.3 ms and 4.9 ± 0.5%. The overall error rate was 5.8 ± 0.3%. The mean response latency for errors was 1241 ± 40.0 ms.

The reliable region and distance effects in the response latency data, and the finding that close objects in different regions primed each other significantly more than far objects in different regions, offer support for partially hierarchical theories.

Direction Judgments

In the first analysis, responses were scored as −180° to 180° of deviation from the actual stimulus direction. Vertical and horizontal distortions were scored differently to test for the possibility that the judged direction of an object would be distorted vertically (i.e., the judged direction would be more vertical than the actual direction) when the objects were in regions with a vertical orientation and would be distorted horizontally (i.e., the judged direction would be more horizontal than the actual direction) when the objects were in regions with a horizontal orientation. Deviations in the vertical direction were scored as positive, and deviations in the horizontal direction were scored as negative. Thus, if superordinate spatial relations affected direction judgments, one would expect judgments between objects with vertical superordinates to have positive deviations, on the average, but judgments between objects with horizontal superordinates to have negative deviations, on the average. This scoring procedure is the same as the one used by Stevens and Coupe (1978). Table 3 contains the mean angular deviations between judged and actual directions for each group and each condition. These data do not include judgments between objects in the same region because alignment was not manipulated within regions.

The mean deviations in degrees between judged and actual directions were analyzed. (Because of the scoring procedure, only the effects of superordinate and interactions with superordinate are meaningful. Con-

TABLE 3
Mean Angular Deviations between Judged and Actual Directions in the Direction Judgment Task

	Close		Far	
	Aligned	Misaligned	Aligned	Misaligned
Map				
Vertical	−4.3	26.6	1.3	11.3
Horizontal	7.3	−35.8	0.2	−8.3
Free navigation				
Vertical	15.2	20.5	−3.1	−10.6
Horizontal	−9.7	−34.8	2.6	−9.1
Constrained navigation				
Vertical	−5.6	44.4	−6.1	7.1
Horizontal	−12.9	−48.8	−1.0	−16.3
Overall				
Vertical	1.8	30.5	−2.7	2.6
Horizontal	−5.1	−39.8	0.6	−11.2

sequently, F's for these effects only are presented.) Direction judgments between objects with vertical superordinates tended to be distorted in a vertical direction (mean deviation = 8.0°) and judgments between objects with horizontal superordinates tended to be distorted in a horizontal direction (mean deviation = −13.9°), $F(1,69) = 61.05$, $p < .0001$. There also were reliable interactions between superordinate and distance, $F(1,69) = 41.07$, $p < .0001$, between superordinate and alignment, $F(1,69) = 79.50$, $p < .0001$, and between superordinate, distance, and alignment, $F(1,69) = 22.67$, $p < .0001$. The three-way interaction was produced because direction judgments were distorted more for misaligned than for aligned objects, and because the size of this difference was much larger for close objects than for far objects. (This pattern held for both levels of superordinate. The three-way interaction was caused because vertical distortions were scored to have positive values, which meant that large distortions were indicated by large positive numbers, whereas horizontal distortions were scored to have negative values, which meant that large distortions were indicated by very small negative numbers.) The interaction between group, superordinate, and distance was marginally significant, $F(2,69) = 3.11$, $p = .051$; and the interaction between group, superordinate, and alignment was statistically significant, $F(2,69) = 6.94$, $p < .005$. However, the four-way interaction between these effects was not reliable, $F(2,69) = 1.08$. All in all, the three groups showed very similar patterns of results in the direction judgment task.

To verify that distortions in direction judgments were not produced

TABLE 4
Mean Deviations in Feet between Estimated and Actual Distances in the Distance Estimation Task

	Same region		Different regions			
			Close		Far	
	Close	Far	+	−	+	−
Map	0.52 (−.38)	0.12 (−.49)	1.9 (.71)	2.1 (.80)	0.54 (−.18)	0.18 (−.46)
Free navigation	−0.30 (.18)	−1.0 (−.48)	0.05 (.61)	−0.20 (.32)	−1.0 (−.72)	−0.41 (.09)
Constrained navigation	−0.45 (−.42)	−0.91 (−.69)	0.74 (.86)	0.40 (.44)	−0.42 (−.31)	−0.23 (.12)
Overall	−0.08 (−.21)	−0.60 (−.55)	0.91 (.73)	0.77 (.52)	−0.30 (−.40)	−0.15 (−.08)

Note. Values in parentheses are means computed after standardizing within subjects to a mean of 0 and a variance of 1. All analyses reported in the text were performed on these standardized values. + = Aligned; − = misaligned.

because subjects guessed on difficult items, the mean confidence ratings (computed for each subject and each condition) were analyzed. In general, confidence ratings went in the opposite direction as location judgments. For example, whereas subjects were less accurate on misaligned than on aligned locations, subjects were slightly more confident on misaligned locations (M = 7.3) than on aligned locations (M = 7.1), $F(1,69) = 7.00$, $p < .025$.

Analyses of direction judgments showed that subjects in all three groups distorted spatial judgments to correspond with superordinate spatial relations. Further, the sizes of these distortions depended on the distances between objects: When objects were close together, subjects greatly distorted spatial judgments between misaligned objects, but when objects were far apart, these distortions virtually disappeared. Confidence ratings indicated that the effects of superordinates on direction judgments could not be attributed to guessing on difficult items.

Distance Estimations

The mean deviations between estimated and actual distances were computed for each subject and each condition. Table 4 contains these data for each group, collapsed across subjects. To adjust for differences in scale across subjects, each subject's mean deviations (six per subject) were standardized to a mean of 0 and a variance of 1. The means of these standardized scores are presented in parentheses next to the raw means in Table 4. Analyses were performed on both the raw scores and the standardized scores. These analyses produced very similar patterns of results. Because I was primarily interested in the differential effects of the experimental conditions on distance estimations, and not in overall accuracy, only analyses of the standardized scores are presented.

The first analysis examined the effects of distance and alignment on distance estimations between objects in different regions. Subjects tended to overestimate distances between close objects in different regions ($M = .62$), relative to their mean deviations, but underestimate distances between far objects in different regions ($M = -.24$), relative to their mean deviations, $F(1,69) = 61.90$, $p < .0001$. In addition, the overall mean deviations for the map and constrained-navigation groups were larger than the overall mean for the free-navigation group, $F(2,69) = 4.22$, $p < .025$. The interaction between distance and alignment was significant, $F(1,69) = 6.57$, $p < .025$, as was the three-way interaction between group, distance, and alignment, $F(2,69) = 4.75$, $p < .025$. An inspection of these data indicated that distance and alignment interacted for the direct-experience groups but not for the map group. An interaction contrast comparing the distance × alignment interaction in the direct-experience groups (weighted equally) to the distance × alignment interaction in the map group was statistically reliable, $F(1,69) = 9.29$, $p < .005$, and accounted for 98% of the variance attributable to the three-way interaction.

The interaction between distance and alignment for the direct-experience groups can be explained by noting that distances between objects and boundaries were larger for aligned than for misaligned objects and that subjects' knowledge of the locations of objects was quite inaccurate. If we align the stapler and boat (see Fig. 2) but keep their distances from the boundary constant, the physical distance between these objects is less than the physical distance between objects that actually are aligned. If subjects "aligned" misaligned objects in their memories (and direction judgments indicated that they did) and also encoded that close-misaligned objects were closer to region boundaries than close-aligned objects, subjects' distance estimations would mirror the physical events. Far objects in different regions would not show the same pattern because subjects had a better idea where these objects were in relation to other objects. Moreover, subjects probably did not encode the positions of these objects relative to region boundaries because the objects were reasonably far from the boundaries. Why these variables did not interact for the map group is not clear; possibly because the relative distances between objects and boundaries were too small on the maps to be noticed.

An important analysis for testing the theories of spatial representations was to examine the effects of region boundaries on distance estimations.

To this end, the standardized scores were collapsed across alignment. This procedure was deemed appropriate, despite the reliable interaction between alignment and distance, because the ordinal relations between mean deviations in the close condition and mean deviations in the far condition were preserved.

These analyses revealed that subjects underestimated distances between objects in the same region ($M = -.38$) and overestimated distances between objects in different regions ($M = .19$), $F(1,69) = 42.67$, $p < .0001$. In addition, subjects overestimated distances between close objects ($M = .21$) and underestimated distances between far objects ($M = -.40$), $F(1,69) = 35.34$, $p < .0001$. The size of this distance effect was smaller when objects were in the same region (mean difference = .35) than when objects were in different regions (mean difference = .86), $F(1,69) = 12.16$, $p < .001$. The main effect of group was statistically reliable, $F(2,69) = 4.22$, $p < .025$, which simply reflected that the overall means for the map and constrained-navigation groups were somewhat smaller than the mean for the free-navigation group. There was also a reliable interaction between group and region, $F(2,69) = 4.22$, $p < .025$, indicating that the size, but not the direction, of the region effect differed across groups. No other effects were statistically reliable.

Two aspects of these data immediately support hierarchical theories: First, subjects underestimated distances between objects in the same region (relative to their mean deviations); and second, subjects overestimated distances between objects in different regions (again, relative to their mean deviations).

Individual Differences

Individual differences in the patterns of results did not emerge in any of the tasks nor for any of the groups. The number of trials needed to learn each of the layouts was correlated with scores on the DAT and the Vandenberg. These correlations did not reveal any consistent patterns. Moreover, there were no significant correlations between performance in any of the three tasks and the ability tests.

The mean scores on the DAT (maximum = 50) were 43.0 for the map group, 43.5 for the free-navigation group, and 44.6 for the constrained-navigation group, $F < 1$. Overall, sexes did not differ significantly on the DAT, $F < 1$. The overall mean and standard deviation on the DAT were 43.7 and 5.6, respectively. Mean scores on the Vandenberg (maximum = 20) were 13.6 for the map group, 11.7 for the free-navigation group, and 13.0 for the constrained-navigation group, $F < 1$. Sexes differed significantly on the Vandenberg, $F(1,66) = 11.06$, $p < .005$. Means were 14.3

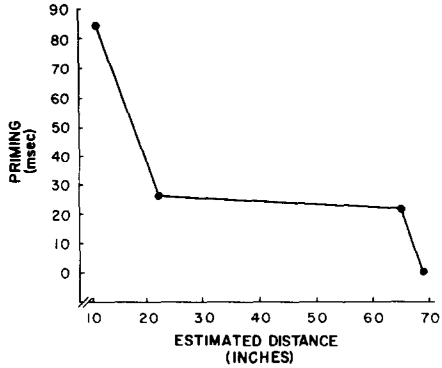

FIG. 5. The sizes of priming effects as a function of estimated distances. Response latencies were scaled against the condition with the longest mean latency, different regions/far apart.

for males and 11.2 for females. The overall mean and standard deviation on the Vandenberg were 12.8 and 4.2, respectively.

DISCUSSION

Overall, results from the experiment provide a coherent picture of the mental representation of knowledge acquired from maps and from direct experience. The results from all three tasks, and for all three groups of subjects, supported partially hierarchical theories.

The priming result most relevant for distinguishing partially hierarchical theories from nonhierarchical theories was the finding that locations in the same region primed each other more than locations in different regions. This result indicates that locations in the same region were "closer" in subjects' memories than locations in different regions, regardless of euclidean distance. This interpretation is consistent with the principal claim of partially hierarchical theories: that different regions of an environment are stored in different branches of a partially hierarchical mental representation.

Nonhierarchical theories might be able to handle the priming results if one assumed that subjects' cognitive maps were systematically distorted. In particular, if distances between objects in different regions were expanded in memory and if activation decayed appropriately as a function of these psychological distances, nonhierarchical theories might predict the patterns of results obtained in the experiment. The relation between activation levels and psychological distances can be tested indirectly by examining the sizes of priming effects as a function of estimated distances. These data are plotted in Fig. 5. The sizes of priming effects were estimated by subtracting the mean response latency for each condition from the mean for the different regions/far condition (790 ms). This procedure will underestimate absolute priming effects to the extent that decisions in the different regions/far condition were primed (relative to a neutral control).

The shape of the function in Fig. 5 is extremely difficult for nonhierarchical theories to predict a priori. The problem is the precipitous decline in priming between the third point (same region/far) and the fourth point (different regions/far). These points differ by only 4 in. in estimated distances. (This decline in priming is not due to error of measurement, since response latencies corresponding to the second and third points differed reliably from those corresponding to the fourth.) A nonhierarchical theory in which spatial knowledge was encoded in simple networks would predict an exponential decay of priming with psychological distances (Anderson & Pirolli, 1984; Ratcliff & McKoon, 1981b). One might be able to account for the step function in Fig. 5 by postulating an appropriate relationship between psychological and estimated distances. For example, a model could be constructed in which psychological distances between objects were much larger in the different regions/far condition than in the same region/far condition, but a nonlinear (e.g., logarithmic) transformation mapped those large differences onto small ones (thus creating a large difference in priming over a relatively small range of estimated distances). It is not at all clear, however, that any such transformation could be constructed so that it was consistent with the other estimated distances and their accompanying priming effects. Indeed, the relation in Fig. 5 is very compatible with partially hierarchical theories, as is shown below.

The result most relevant for distinguishing partially hierarchical theories from strongly hierarchical theories and the theory proposed by Stevens and Coupe (1978) was the reliable effect of distance on priming across region boundaries. This result shows that subjects were encoding spatial relations across region boundaries.

The direction judgment task, like the priming task, produced very similar patterns of results across the three groups. Namely, subjects distorted direction judgments to correspond with the spatial relations between superordinate regions, confirming results of previous research (Stevens & Coupe, 1978), and they did so more for short distances than for long distances. This experiment replicated results reported by Stevens and Coupe (1978) and yet showed, in the priming task, that subjects were encoding spatial relations across region boundaries. Taken together, these results suggest that the distortions observed by Stevens and Coupe were not caused by the absence of encoded spatial relations across region boundaries.

The interaction between distance and alignment in direction judgments suggests a possible way to account for distortions in judged spatial relations. Recall from the introduction, that under hierarchical theories, direction judgments might be distorted because higher order spatial information was weighted heavily by inference processes or because location information was inaccurately encoded. Direction judgments suggest that inaccuracies in location information were causing at least some of these distortions. An explanation solely based on superordinate spatial relations would have to explain why superordinate information was heavily weighted when objects were close together but not when objects were far apart. But consider the effects of inaccurate location knowledge on direction estimates: When objects are close together, even minor perturbations of their positions will produce large changes in relative orientation; but when objects are far apart, these same perturbations will produce very small changes in orientation. In short, inaccurate location knowledge is less useful when objects are close together than when objects are far apart.

Results from the distance estimation task also supported hierarchical theories (although they could not, by themselves, distinguish between strongly and partially hierarchical theories). For example, subjects consistently overestimated distances between close objects in different regions (relative to their mean deviations). This effect is somewhat unusual, in that transparent boundary effects on distance estimations have been found for children (Kosslyn et al., 1974) but not for adults (Kosslyn et al., 1974; Newcombe & Liben, 1982). Boundary effects are consistent with hierarchical theories, since under these theories, distance estimations should be a function of the encoded distance between objects and of whether objects are in the same region or in different regions.

Distances between far locations in different regions were not, generally, overestimated. This outcome was probably caused by the interaction between hierarchical encoding and a phenomenon often found in magnitude estimations—regression of estimates toward the mean. An example of regression in distance estimation is that subjects typically overestimate distances between close objects and underestimate distances between far objects (McNamara et al., 1984; Newcombe & Liben, 1982). The results from this experiment are consistent with the simultaneous operation of hierarchical encoding and regression in magnitude estimation. When subjects estimated distances between *close* objects in different regions, both hierarchical encoding and regression were working in the same direction, viz., to increase estimates. However, when subjects estimated distances between *far* objects in different regions, hierarchical encoding contributed to increasing estimates, but regression contributed to decreasing estimates. Under this view, extreme points should occur when hierarchical encoding and regression are working in the same direction. In fact, this is exactly what happened: Extreme values appeared for far objects in the same region (both hierarchical encoding and regression have the effect of reducing estimates) and for close objects in different regions (both hierarchical encoding and regression have the effect of increasing estimates).

The last major finding in the experiment concerned the effects of functional distance on cognitive maps. The highly similar patterns of results between the free- and constrained-navigation groups suggest that when visual distance is equated, functional distance alone has little effect on the mental representation and processing of spatial relations.

SIMULATIONS

These empirical results support partially hierarchical theories. Nevertheless, it is important to demonstrate that a mathematically explicit version of such a theory could predict the major results of the experiment. To this end, I constructed a parametric description of a partially hierarchical theory and generated predictions for performance in the recognition task. This task was chosen over the others because there are many theoretical tools available for predicting retrieval times in recognition and because it seemed to be the most important one for distinguishing the theories.

Conceptual Overview

The model proposes that subjects encode the spatial relations among four classes of environmental features: objects, the region boundaries, the regions themselves, and the layout as a whole.

At the "lowest" level of the representation, there is some probability that a subject will encode in memory the spatial relations between two objects (e.g., the watch and pipe) or between an object and a region boundary (e.g., the gun and the boundary below it; see Fig. 2). These probabilities decay with distance and the rate of decay is greater for objects in different regions than for objects in the same region. So, for example, the probability of encoding spatial relations between the key and spool is much higher than between the watch and pipe (.99 vs .05 in the current model) and is higher between the needle and wallet than between the gun and chalk (.37 vs essentially 0). Additionally, it is assumed that subjects encode spatial relations (with probability 1) between region boundaries that "touch" but not otherwise. Encoding spatial relations in memory corresponds to encoding objects, boundaries, or both, in the same spatial image "unit" (Anderson, 1983) or "chunk" (Miller, 1956). This fact is captured in the model by specifying a link between the nodes in memory corresponding to the objects or boundaries.

At the "middle" level of the representation, each object is encoded as being in one of the four regions (always the correct one). The model proposes that there is a node in memory corresponding to each region in the layout. Links between location nodes and region nodes specify the positions of the locations in their respective regions. Region boundaries are encoded as being in the appropriate regions, with the added fact that interior boundaries (e.g., separating the needle and wallet) are encoded as being in *two* regions, viz., the two regions separated by the boundary.

At the "topmost" level of the representation, each region is encoded as part of the spatial layout (or map). According to the model, there is a single node in memory corresponding to an entire layout and each region node is linked to that layout node.

Under this model, the mental representation of one of the layouts would contain 49 nodes: 32 for the objects; 12 for the region boundaries; 4 for the regions; and 1 for the entire layout.

This structural model and the spreading activation process developed by Anderson (1983) were used to predict activation levels of memory traces in a recognition test. According to the model, when a memory trace (a "node") becomes a source of activation (as it would if the stimulus corresponding to that trace were perceptually available), activation spreads from this source throughout memory. The spread of activation is hypothesized to be extremely fast (cf. Anderson, 1976); an asymptotic pattern of activation is established in as little as 100 ms (Anderson & Pirolli, 1984). The critical variable influencing retrieval times is asymptotic activation level. All else equal, more active memory traces are retrieved faster than less active ones. The asymptotic activation of a trace is a function of (a) its strength, (b) its strength relative to the strength of other traces in memory, and (c) its "distance" from a source of activation.

Although the model could have been used to predict actual retrieval times, I chose not to do so for two reasons. First, the values of parameters, and consequently predicted retrieval times, would depend critically on the function defining the probability of encoding spatial relations (see Eq. (1) below). There is no independent justification for the exact form of this function, so it seemed premature to assume one. Second, predicting retrieval times would require strong assumptions about the function (or functions) relating activation levels in memory to processing times.

Mathematical Development

For present purposes, I have assumed that the probability of encoding the spatial relations between two locations, i and k, decays exponentially with the distance between them. The equation is

$$p_{ik} = \exp[-(d_{ik}/l)^a] \quad (1)$$

where p_{ik} is the probability of encoding the spatial relations between locations i and k; d_{ik} is the euclidean distance between these locations; l is a scaling parameter; and a is the rate of decay (for fixed l). (The reader may recognize Eq. (1) as the survivor function for a Weibull distribution.) This function was chosen for three reasons. First, it is "scale free." That is, the shape of the function can be maintained across layouts of different scales (e.g., maps vs real spatial layouts) by adjusting l. Second, the function has an intuitively reasonable shape, the complement of an ogive. That is, probability is high for a small range of distances, and then drops off rapidly beyond a given distance.The range of high probabilities and the rate of decay are determined by l and a. Third, and finally, the effects of boundaries can be captured in the model by manipulating the value of l (for an environment of fixed scale). (This fact is demonstrated below.) In spite of these reasons, I am not firmly committed to this particular function; there are many alternatives that could produce equivalent results.

In order to model activation levels, it is necessary to specify the strengths of memory traces. Strength is a function of number of rehearsals. There is no way to know how many times subjects rehearsed the locations of objects in this experiment. I hypothesized that subjects would be able to rehearse each location approximately twice during a study session. Since subjects required about four study sessions on the average, we can estimate that total strength was approximately eight units (where one unit was accrued for each rehearsal). In the interest of limiting the number of potentially free parameters, I chose to set the strengths of all nodes to eight units. (One might elect to set the strength of the filler nodes—i.e., nodes corresponding to the filler locations in a layout—to a smaller value, such as 1, since subjects were not required to learn the locations of these objects. This manipulation produced trivially better fits.)

Finally, to guarantee that activation will asymptote, it is necessary to assume that some activation is lost when it spreads from one node to another. I have assumed that loss is 20% (i.e., 80% of the activation is maintained when it spreads across one link). This value has been used successfully by Anderson (1983).

A node receives activation from two principal sources. First, if a node is a source node, it will receive activation from itself proportional to its strength. Second, each node in memory receives activation from all nodes that it is connected to. The amount of activation that node i receives from node k is proportional to the strength of i relative to all other nodes connected to k. A significant departure is required from the spreading activation process developed by Anderson because of the probabilistic character of the memory representation. In this model, the activation received by node i from node k is also proportional to the probability that these two nodes are linked in memory. These facts can be summarized in the following equation (cf. Anderson, 1983):

$$a_i = c_i + m \cdot \sum_{k} (r_{ik} \, p_{ik} \, a_k) \tag{2}$$

where a_i is the activation level of node i; c_i is equal to the strength of i if i is a source node and zero otherwise; m is the maintenance factor (i.e., the proportion of activation maintained across a link); r_{ik} is the strength of the connection between nodes i and k and is equal to the strength of i divided by the sum of the strengths of all nodes connected to k; p_{ik} is the probability of a link between i and k (given by Eq. (1)); and a_k is the activation level of node k. The relation expressed in Eq. (2) produces a system of n linear equations in n unknowns, which has a unique solution provided that m is less than 1 and that strengths of links (r_{ik}) and probability (p_{ik}) are defined as above (Protter & Morrey, 1964).

At this point, the only free parameters in the model are l and a. Based on interviews with subjects in a different, but related, experiment, I estimated that the probability of encoding spatial relations between locations was virtually 1.0 for close objects in the same region; was .05 to .10 for far objects in the same region; was .3 to .4 for close objects in different regions; and was virtually 0 for far objects in different regions. Using these values as a guide, a was set to 3.18 and l was set to 4.25 for within-region distances and to 1.0 for between-region distances (distances were measured in feet). A nice feature of defining probability with Eq. (1) is that the effects of boundaries are realized in a single, identifiable parameter of the model, l. Experimental manipulations of the saliency of boundaries (say, via physical properties of the boundaries or instructions to subjects) should affect the value of l in a systematic manner.

In summary, the following parameter values were chosen: strengths of all nodes were set to 8; maintenance was set to 0.8; a was set to 3.18; and l was set to 4.25 within regions and 1.0 between regions.

Predictions of the Model

The model predicts activation levels for 98 nodes in memory (49 nodes in each layout) but only a subset of these are of interest here. The nodes of interest are those appearing in the six experimental conditions.

In a primed recognition test like the one used in this experiment, there would be at least three sources of activation on each trial. One source would be the layout node. Activation of this node would be maintained

TABLE 5
Activation Levels Predicted by a Partially Hierarchical Theory

	Same region		Different regions			
			Close		Far	
	Close	Far	+	−	+	−
Activation levels	13.33	11.01	10.92	10.89	9.97	10.19
RL	705	768	773	753	782	797

Note. Latencies are in milliseconds. Units of activation are discussed in the text. + = Aligned; − = misaligned. RL = response latencies.

because of the explicit demands of the recognition test, viz., to decide whether or not some object was in the layout just learned. A second source of activation would be the item on the current trial. The third source of activation would be the item presented on the immediately previous trial, i.e., the "priming" stimulus. According to the model, retrieval times will be an inverse function of activation levels: The more active a node is, the quicker it can be retrieved from memory. Preliminary simulations revealed that the activation of the layout node was virtually constant across conditions. This fact indicates that differences in retrieval times were due to activation levels of the focused location nodes. The average of the "prime" and "target" node activation levels (collapsed across the two layouts) are reported in Table 5, along with observed mean response latencies.

These data demonstrate that a partially hierarchical theory can provide a very good account of the retrieval times. Overall, the observed response latencies correspond quite well to what one would predict based on the activation levels. In fact, there is a strong linear relationship between the two, $r = -.952$, $p < .01$. (This relationship is virtually perfect when these data are collapsed across alignment, $r = -.996$, $p < .01$.) A close examination of these data suggests that the model might be making systematic errors in a couple of places. For example, the model seems to overpredict activation levels in the different regions/far/misaligned condition relative to the different regions/far/aligned condition. However, the mean response latencies for these conditions are not significantly different, so it is not clear whether the model is at fault or we are simply seeing variability in the response latencies. I want to emphasize that these predictions were obtained based on educated guesses for parameter values not on parametric estimation (e.g., via least squares or maximum likelihood). Fits could be improved still further by postulating a functional relationship between activation levels and response latencies and by allowing one or more of the parameters to vary freely.

GENERAL DISCUSSION

Problems with Priming?

The priming task used in this experiment might be criticized on two grounds: One possible criticism is that priming may have been caused by nonspatial associations, such as verbal associations, rather than by spatial knowledge encoded in cognitive maps. McNamara, Ratcliff, and McKoon (1984) tested this hypothesis and showed that nonspatial associations could not account for spatial priming in recognition, at least when subjects learned maps. This result suggests that nonspatial associations also could not account for priming when subjects learn a spatial layout via direct experience.

Another possible problem with the recognition task lies in the relative contributions of strategic and automatic processes (Posner & Snyder, 1975a, 1975b) to priming in spatial memory. Research on memory for text has shown that recognition priming is an automatic process (Ratcliff & McKoon, 1981a), but there has been no comparable research on memory for spatial knowledge. Two observations support the claim that priming in spatial memory is primarily automatic: First, priming in textual memory and priming in spatial memory are produced by the same task, item recognition. Second, the 250-ms response–stimulus interval was sufficiently short to prevent strategic processes from becoming fully active (e.g., Neely, 1977; Posner & Snyder, 1975a, 1975b; Ratcliff & McKoon, 1981a), if they occurred at all. This issue will not be resolved completely until experiments on spatial memory are conducted in which the probability of priming events and the time interval between primes and targets are systematically manipulated.

Related Findings

Partially hierarchical theories have been supported by other experiments as well. For example, there is ample evidence that adults and children overestimate distances between objects separated by opaque barriers (e.g., Cohen, Baldwin, & Sherman, 1978; Kosslyn et al., 1974; Newcombe & Liben, 1982). This finding is consistent with the hypothesis that physical boundaries induce hierarchical encoding of an environment. Maki (1981) has shown that symbolic distance effects (e.g., Evans & Pezdek, 1980; Moyer & Bayer, 1976; Paivio, 1975) are obtained for east–west and north–south judgments between cities in the same state but not between cities in different states. This result indicates that subjects use regional information (category knowledge) to judge relative position when that knowledge is available and useful. In a similar vein, Wilton (1979) has shown that directional statements between regions (England vs Scotland) are verified faster than statements within regions, even when euclidean distance is held constant. Finally, Hirtle and Jonides (1985) have shown that cognitive maps of a natural environment are organized into subjective regions, and that these regions affect subjects' abilities to judge the distances between objects and to draw accurate maps of an environment. Although these data are not conclusive, they are consistent with the hypothesis that spatial environments are encoded in some kind of hierarchical fashion.

Closing Remarks

The experimental results and simulations argue strongly that spatial relations among objects in an artificial environment are encoded in a partial hierarchy. It remains to be seen whether or not partially hierarchical theories will provide an adequate account of spatial knowledge acquired through repeated and varied experiences with a natural environment. At this point, an attempt to generalize these results to knowledge of everyday spatial environments would be premature.

This research has even less to say about mental representations of spatial information in general. There are obvious similarities, however, between the representations explored here and the ones investigated in studies of other kinds of spatial memory. For example, hierarchical representations, broadly defined, have been proposed in theories of mental rotation (e.g., Just & Carpenter, 1976, elaborated in Anderson, 1983) and visual perception, especially the perception of three-dimensional structure (e.g., Marr, 1982; Shepard, 1984). The similarities among these representations may prove to be more apparent than real. But they also may prove to be caused by an essential affinity; one produced, perhaps, by a fundamental principle of coding in human memory.

Although that problem is an important one, it is unlikely to be solved soon. A similar but more tractable problem lies in the structural relations between representations of spatial knowledge and representations of other kinds of knowledge. Clearly, spatial knowledge does not exist in a vacuum. In addition to our knowledge about the locations of objects, we often have extensive nonspatial knowledge about those objects. For example, about a building, we might know the businesses that reside there, the building's architect, and when the building was built. About a city, we might know its size, its industries, and its best (and worst) restaurants. Our knowledge is not limited to facts such as these; we often have strong emotional responses to the architectural style of a building or to the quality of life in a city. Clayton and Woodyard (1981) stated the problem nicely when they said that spatial knowledge should be viewed as "evolving from an autobiography of experiences that happen to take place in space." Investigations of how spatial and nonspatial knowledge are integrated in memory (if they are) might shed light on the general problem of how knowledge in different content domains is organized and integrated in memory. This focus is an important one, since one of the many things that we have learned from research on cognition and artificial intelligence is that expert performance requires a rich, and richly articulated, knowledge base. Research along these lines may help us understand the genesis and structure of these complex interconnections in memory.

APPENDIX

This appendix contains the names of objects used in the experiment and the names of objects used as foils in the recognition test.

Layout A

Experimental Pairs	Foils
Key–spool	Necklace
Match–fork	Flower
Needle–wallet	Record
Stapler–boat	Soap
Zipper–wrench	Box
Hammer–pencil	Brick
Candle–glove	Saw
Watch–pipe	Mug
Saucer–nail	Newspaper
Razor–tack	Tire
Chalk–gun	Lamp
Bowl–tape	Spoon
	Bag
	Cigar
	Sandpaper
	Block

Layout B

Experimental pairs	Foils
Cup–screw	Dish
Cigarettes–ball	Fan
Sock–glue	Comb

Egg–scissors	Towel
Shoe–pen	Chair
Button–can	Pan
Eraser–lightbulb	Ribbon
Radio–envelope	Clock
Book–rubberband	Chain
Cork–truck	Bottle
Flashlight–cufflink	Brush
Knife–ring	Telephone
	Briefcase
	Candy
	Magazine
	Screwdriver

REFERENCES

Acredolo, L. P., Pick, H. L., & Olsen, M. G. (1975). Environmental differentiation and familiarity as determinants of children's memory for spatial location. *Developmental Psychology*, **11**, 495–501.

Anderson, J. R. (1976). *Language, memory, and thought*. Hillsdale, NJ: Erlbaum.

Anderson, J. R. (1978). Arguments concerning representations for mental imagery. *Psychological Review*, **85**, 249–277.

Anderson, J. R. (1983). *The architecture of cognition*. Cambridge, MA: Harvard Univ. Press.

Anderson, J. R., & Pirolli, P. L. (1984). Spread of activation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **10**, 791–798.

Anooshian, L., & Young, D. (1981). Developmental changes in cognitive maps of a familiar neighborhood. *Child Development*, **52**, 341–348.

Appleyard, D. (1970). Styles and methods of structuring a city. *Environment and Behavior*, **2**, 100–118.

Baird, J. C., Merrill, A., & Tannenbaum, J. (1979). Studies of the cognitive representation of spatial relations. II. A familiar environment. *Journal of Experimental Psychology: General*, **108**, 92–98.

Bennett, G. K., Seashore, H. G., & Wesman, A. G. (1974). Differential Aptitude Tests-Form T. New York: The Psychological Corporation.

Byrne, R. W. (1979). Memory for urban geography. *Quarterly Journal of Experimental Psychology*, **31**, 147–154.

Clayton, K., & Chattin, D. (1981). *Priming effects in tests of spatial knowledge*. Paper presented at the Fifty-third Annual Meeting of the Midwestern Psychological Association. Detroit, MI.

Clayton, K., & Woodyard, M. (1981). The acquisition and utilization of spatial knowledge. In J. Harvey (Ed.), *Cognition, social behavior, and the environment*. Hillsdale, NJ: Erlbaum.

Cohen, R., Baldwin, L. M., & Sherman, R. C. (1978). Cognitive maps of a naturalistic setting. *Child Development*, **49**, 1216–1218.

Cohen, R., & Weatherford, D. L. (1980). Effects of route traveled on the distance estimates of children and adults. *Journal of Experimental Child Psychology*, **29**, 403–412.

Davis, E. (1981). *Organizing spatial knowledge*. Yale University Department of Computer Science Research Rep. 193.

Downs, R. M. (1981). Maps and mapping as metaphors for spatial representation. In L. S. Liben, A. H. Patterson, & N. Newcombe (Eds.), *Spatial representation and behavior across the life span*. New York: Academic Press.

Evans, G. W., & Pezdek, K. (1980). Cognitive mapping: Knowledge of real-world distance and location information. *Journal of Experimental Psychology: Human Learning and Memory*, **6**, 13–24.

Glass, A. L., & Holyoak, K. J. (1975). Alternative conceptions of semantic memory. *Cognition*, **3**, 313–339.

Hardwick, D. A., McIntyre, C. W., & Pick, H. L. (1976). The content and manipulation of cognitive maps in children and adults. *Monographs of the Society for Research in Child Development*, **41**(3, Serial No. 166).

Hintzman, D. L., O'Dell, C. S., & Arndt, D. R. (1981). Orientation in cognitive maps. *Cognitive Psychology*, **13**, 149–206.

Hirtle, S. C., & Jonides, J. (1985). Evidence of hierarchies in cognitive maps. *Memory & Cognition*, **13**, 208–217.

Johnson-Laird, P. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness*. Cambridge, England: Cambridge Univ. Press.

Just, M. A., & Carpenter, P. A. (1976). Eye fixations and cognitive processes. *Cognitive Psychology*, **8**, 441–480.

Kosslyn, S. M. (1975). Information representation in visual images. *Cognitive Psychology*, **7**, 341–371.

Kosslyn, S. M., Ball, T. M., & Reiser, B. J. (1978). Visual images preserve metric spatial information: Evidence from studies of image scanning. *Journal of Experimental Psychology: Human Perception and Performance*, **4**, 47–60.

Kosslyn, S. M., Pick, H. L., & Fariello, G. R. (1974). Cognitive maps in children and men. *Child Development*, **45**, 707–716.

Kosslyn, S. M., & Pomerantz, J. R. (1977). Imagery, propositions, and the form of internal representations. *Cognitive Psychology*, **9**, 52–76.

Kosslyn, S. M., & Shwartz, S. P. (1977). A simulation of visual imagery. *Cognitive Science*, **1**, 265–295.

Kozlowski, L., & Bryant, K. (1977). Sense of direction, spatial orientation, and cognitive maps. *Journal of Experimental Psychology: Human Perception and Performance*, **3**, 590–598.

Kuipers, B. (1978). Modeling spatial knowledge. *Cognitive Science*, **2**, 129–153.

Levine, M., Jankovic, I., & Palij, M. (1982). Principles of spatial problem solving. *Journal of Experimental Psychology: General*, **111**, 157–175.

Liben, L. S. (1981). Spatial representation and behavior: Multiple perspectives. In L. S. Liben, A. H. Patterson, & N. Newcombe (Eds.), *Spatial representation and behavior across the life span*. New York: Academic Press.

Liben, L. S. (1982). Children's large-scale spatial cognition: Is the measure the message? In R. Cohen (Ed.), *New directions for child development: Children's conceptions of spatial relationships*, No. 15. San Francisco: Jossey–Bass.

Lynch, K. (1960). *The image of the city*. Cambridge, MA: MIT Press.

Maki, R. H. (1981). Categorization and distance effects with spatial linear orders. *Journal of Experimental Psychology: Human Learning and Memory*, **7**, 15–32.

Marr, D. (1982). *Vision*. San Francisco: Freeman.

McDermott, D. (1981). *Finding objects with given spatial properties*. Yale University Department of Computer Science Research Rep. 195.

McNamara, T. P., Ratcliff, R., & McKoon, G. (1984). The mental representation of knowledge acquired from maps. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **10**, 723–732.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, **63**, 81–97.

Moyer, R. S., & Bayer, R. H. (1976). Mental comparison and the symbolic distance effect. *Cognitive Psychology*, **8**, 228–246.

Neely, J. H. (1977). Semantic priming and retrieval from lexical memory: Roles of inhibitionless spreading activation and limited capacity attention. *Journal of Experimental Psychology: General*, **106**, 226–254.

Newcombe, N. (1981). Spatial representation and behavior: Retrospect and prospect. In L. S. Liben, A. H. Patterson, & N. Newcombe (Eds.), *Spatial representation and behavior across the life span*. New York: Academic Press.

Newcombe, N., & Liben, L. S. (1982). Barrier effects in the cognitive maps of children and adults. *Journal of Experimental Child Psychology*, **34**, 46–58.

Paivio, A. (1975). Perceptual comparisons through the mind's eye. *Memory & Cognition*, **3**, 635–647.

Piaget, J., Inhelder, B., & Szeminska, A. (1960). *The child's conception of geometry*. New York: Basic.

Pick, H. L., & Lockman, J. J. (1981). From frames of reference to spatial representations. In L. S. Liben, A. H. Patterson, & N. Newcombe (Eds.), *Spatial representation and behavior across the life span*. New York: Academic Press.

Posner, M. I., & Snyder, C. R. (1975a). Attention and cognitive control. In R. L. Solso (Ed.), *Information processing and cognition*. Hillsdale, NJ: Erlbaum.

Posner, M. I., & Snyder, C. R. (1975b). Facilitation and inhibition in the processing of signals. In P. M. A. Rabbitt (Ed.), *Attention and performance* (Vol. 5). New York/London: Academic Press.

Presson, C. C., & Hazelrigg, M. D. (1984). Building spatial representations through primary and secondary learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **10**, 716–722.

Protter, M. H., & Morrey, C. B. (1964). *Modern mathematical analysis*. Reading, MA: Addison–Wesley.

Pylyshyn, Z. W. (1973). What the mind's eye tells the mind's brain: A critique of mental imagery. *Psychological Bulletin*, **80**, 1–24.

Ratcliff, R., & McKoon, G. (1981a). Automatic and strategic priming in recognition. *Journal of Verbal Learning and Verbal Behavior*, **20**, 204–215.

Ratcliff, R., & McKoon, G. (1981b). Does activation really spread? *Psychological Review*, **88**, 454–462.

Rieser, J. J., Lockman, J. J., & Pick, H. L. (1980). The role of visual experience in knowledge of spatial layout. *Perception & Psychophysics*, **28**, 185–190.

Schustack, M. (1981). *Word-meaning comprehension: Syntactic and associative effects of sentential context*. Doctoral dissertation, Carnegie–Mellon University.

Shepard, R. N. (1975). Form, formation, and transformation of internal representations. In R. Solso (Ed.), *Information processing and cognition: The Loyola Symposium*. Hillsdale, NJ: Erlbaum.

Shepard, R. N. (1981). Psychophysical complementarity. In M. Kubovy & J. Pomerantz (Eds.), *Perceptual organization*. Hillsdale, NJ: Erlbaum.

Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imagining, thinking, and dreaming. *Psychological Review*, **91**, 417–447.

Siegel, A. W. (1981). The externalization of cognitive maps by children and adults: In search of ways to ask better questions. In L. S. Liben, A. H. Patterson, & N. Newcombe (Eds.), *Spatial representation and behavior across the life span*. New York: Academic Press.

Siegel, A. W., & White, S. H. (1975). The development of spatial representation of large-scale environments. In H. W. Reese (Ed.), *Advances in child development and behavior*. New York: Academic Press.

Smith, E. E. (1978). Theories of semantic memory. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes* (Vol. 6). Hillsdale, NJ: Erlbaum.

Smith, E. E., Shoben, E. J., & Rips, L. J. (1974). Structure and process in semantic memory: A featural model for semantic decisions. *Psychological Review*, **81**, 214–241.

Stevens, A., & Coupe, P. (1978). Distortions in judged spatial relations. *Cognitive Psychology*, **10**, 422–437.

Thorndyke, P. W. (1981). Distance estimation from cognitive maps. *Cognitive Psychology*, **13**, 526–550.

Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology*, **14**, 560–589.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, **55**, 189–208.

Tukey, J. W. (1977). *Exploratory data analysis*. Reading, MA: Addison–Wesley.

Tversky, B. (1981). Distortions in memory for maps. *Cognitive Psychology*, **13**, 407–433.

Vandenberg, S. (1971). *A test of three-dimensional visual spatialization*.

Wilton, R. N. (1979). Knowledge of spatial relations: The specification of the information used in making inferences. *Quarterly Journal of Experimental Psychology*, **31**, 133–146.

(Accepted August 8, 1985)