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Individual Differences in Procedures for Knowledge Acquisition from Maps

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This study investigated the procedures subjects use to acquire knowledge from maps. In Experiment 1, three experienced and five novice map users provided verbal protocols while attempting to learn a map. The protocols suggested four categories of processes that subjects invoked during learning: attention, encoding, evaluation, and control. Good learners differed from poor learners primarily in their techniques for and success at encoding spatial information, their ability to accurately evaluate their learning progress, and their ability to focus attention on unlearned information. An analysis of the performance of experienced map users suggested that learning depended on particular procedures and not on familiarity with the task. In Experiment 2, subjects were instructed to use (a) six of the effective learning procedures from Experiment 1, (b) six procedures unrelated to learning success, or (c) their own techniques. The effective procedures set comprised three techniques for learning spatial information, two techniques for using self-generated feedback to guide subsequent study behaviors, and a procedure for partitioning the map into sections. Subjects using these procedures performed better than subjects in the other groups. In addition, subjects' visual memory ability predicted the magnitude of the performance differential.

Everyone has extensive knowledge of the names and locations of objects in their environment. Maps are a frequent source of such knowledge, for they display in a concise symbolism both explicit information about object names, shapes, and locations, and implicit information about spatial relationships and distances among objects.

People often memorize part or all of a map in order to perform such tasks as selecting routes, navigating between points, identifying land features in the terrain, and estimating distances between locations. This paper examines the processes people use to acquire knowledge from maps and the relationship between those processes and successful learning performance. Our goals are to identify the learning techniques people use when studying a map, to determine whether these techniques influence the rate of knowledge acquisition, and to account for differential success among individuals. These goals lead us to consider several related questions: Are there large individual differences in map learning performance?

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Do people use numerous and diverse study procedures? What distinguishes good learners from poor learners? How do experienced map users differ from novice map users in their learning techniques?

THE MAP LEARNING PROBLEM

For our purposes we have defined a "map" to be a symbolic two-dimensional representation of an area large enough for a person to navigate (e.g., a building, city, country, or continent). We view map learning, like other learning tasks, as a constructive process that produces in long-term memory a representation of the stimulus. While many processes required to learn a map undoubtedly occur in other experimental learning contexts, the map learning task differs in two important ways. First, a map is more complex than typical experimental materials. Learning a typical map requires apprehending and memorizing a set of named objects and places, their shapes and physical extent, and their absolute and relative positions on the map. For example, a red line symbolizing a highway has a name and a two-dimensional spatial representation providing information about shape, distance, capacity, and direction. In addition, other spatial information is portrayed by the relationships between the highway and other elements on the map, such as the intersection of two highways or the location of a building adjacent to the highway. The learning task requires strategies for acquiring and integrating all of this conceptual and spatial information. In contrast, typical learning studies utilize either purely spatial or visual stimuli (e.g., photographs, faces, shapes) or purely verbal stimuli (e.g., lists of words, sentences, texts).

The second unique characteristic of a map learning task is that all information to be learned is presented simultaneously. In many learning paradigms, the stimuli comprise several items presented sequentially to the subject. When learning a map, however, the subject views the entire configuration of information simultaneously. The subject must decide how to selectively attend to subsets of the available information, how much time to spend studying portions of the information, and how many times to study different portions of the information. This flexibility makes the learning problem similar to natural learning situations.

Following many other theories of human cognition (e.g., Newell & Simon, 1972; Anderson & Bower, 1973; Hunt, 1978), we assume that the construction of a memory representation depends upon an existing body of semantic knowledge and a collection of processes. The processes include those that control perceptual focus of attention, encode new knowledge, combine and transform knowledge into new concepts and relationships, and integrate new and previously acquired knowledge. These processes operate in memory at varying levels of abstraction. At the lowest levels, there are mechanistic processes (Posner & Snyder, 1975; Hunt, 1978) that operate on the physical representation of a symbol and are independent of the knowledge denoted by the symbol. Such processes are either automatic (e.g., decoding a linguistic string, recognizing the meaning of a familiar word) or controlled (e.g., manipulating focus of attention on sensory channels, manipulating information in active memory). The controlled processes may be selected and monitored by learners depending upon their knowledge of and skill at using various techniques. At higher levels, there are knowledge-based processes—additional controlled processes whose use depends upon comprehension of the meaning of the information being manipulated. For example, one might decide to learn a list of words by creating semantic categories into which subsets of the words fit. Such high-level, controlled learning techniques may vary widely across individuals, materials, and tasks.

While a growing body of literature has examined individual differences in mechanistic information processes, particularly linguistic processes (Hunt, Frost, & Lunneborg, 1973; Hunt, Lunneborg, & Lewis, 1975; Hunt, 1978; Jackson & McClelland, 1978), little research has examined differences in knowledge-based techniques. A few studies of immediate recall have considered the relationship between linguistic memory and the use of techniques such as imagery (Paivio, 1971; Rohwer, 1973) and chunking (Bower & Winsenz, 1969; Estes, 1974; Lyon, 1977; Cohen & Sandberg, 1977; Voss, 1978). In addition, studies of problem solving have investigated various solution strategies (Newell & Simon, 1972; Mayer & Greeno, 1972; Mayer, 1975; Johnson, 1978).[1] However, research on learning techniques in other task domains has largely ignored individual differences.

In Experiment 1, we collected protocols from subjects attempting to learn a map in order to investigate individual differences in controlled learning procedures. We had several hypotheses that we hoped to verify in the protocols. First, we anticipated that differences in learning performance could be traced to differences in controlled (both mechanistic and knowledge based) processing procedures. If certain procedures are particularly useful for learning, then subjects who use these procedures should perform better than subjects who do not. This condition might arise in two ways. Good learners might use more procedures than poor learners, including those most advantageous for learning. Alternatively,

[1] For the remainder of this paper, we shall use the terms "procedures" and "techniques" to refer to methods that people use to select, elaborate, and encode information in memory (e.g., imagery, rehearsal, etc.). Such processing methods are frequently referred to as "strategies" in the memory literature. However, this term in the problem solving and concept learning literature (e.g., Bruner, Goodnow, & Austin, 1956; Newell & Simon, 1972) typically refers to a general approach to the task or plan for proceeding. Such an approach may specify which "procedures" to use and when to switch among them. To avoid semantic ambiguity, we shall reserve the term "strategy" for such global decisions and use "procedure" to describe individual processing methods.

poor learners might use as many but less effective procedures as good learners.

Prior research has suggested that spatial and verbal information have different memory representations (Brooks, 1968; Shepard, 1975; Baddeley, Grant, Wight, & Thomson, 1975; Kosslyn, 1975, 1976; Kosslyn & Pomerantz, 1977). Since a map contains both spatial and verbal information, we expected that subjects would use different *encoding* procedures for learning information of the two types. Thus, subjects should switch among a variety of procedures for learning information depending on the type of information on which they are focusing.

Finally, we were interested in contrasting the procedures used by experienced map users with those used by novices. We expected the performance of experienced users to be superior to that of novices for one of two reasons. Experts may develop specialized processing techniques that are particularly useful for using maps. Alternatively, experts might perform the same operations as novices, but they might perform those operations faster and more efficiently because of their familiarity with the task.

EXPERIMENT 1

Method

Materials

We constructed two fictitious maps for use as learning materials. The Town Map, shown in Fig. 1, portrayed a river, streets, buildings, parks, and other typical landmarks. All but one of these conceptual elements had names associated with them. The Countries Map, shown in Fig. 2, differed in both scale and content. The map portrayed countries, cities, roads, railroads, and prominent terrain features. Roads and railroads did not have verbal labels, but the other map elements were named. In constructing the maps we attempted to present a variety of types of map features, to include named and unnamed elements, and to make the maps as natural as possible.

Subjects

Eight subjects participated in the study. Five were UCLA undergraduates (three females and two males) who participated to satisfy a course requirement. The remaining three subjects (all males) were chosen because they had extensive professional experience using maps. The "experienced" subjects included DW, a retired Army officer who had field map-using experience and had taught map reckoning to recruits; FK, a retired Air Force pilot with extensive military experience with maps; and NN, a scientist who regularly used graphics display systems for geographic data bases and had been an amateur cartographer for a number of years. All of these individuals frequently used maps in their current jobs.

Procedure

Subjects were tested individually. They were told that they would be shown a map in a series of six study–recall trials. Their task was to learn, using any techniques they knew, the information in the map well enough to draw the map and answer questions about its contents. During study trials they were required to "think aloud" about what they were looking at, what they were thinking about, what their techniques were for focusing their attention on and learning the information in the map, and how well they thought they were

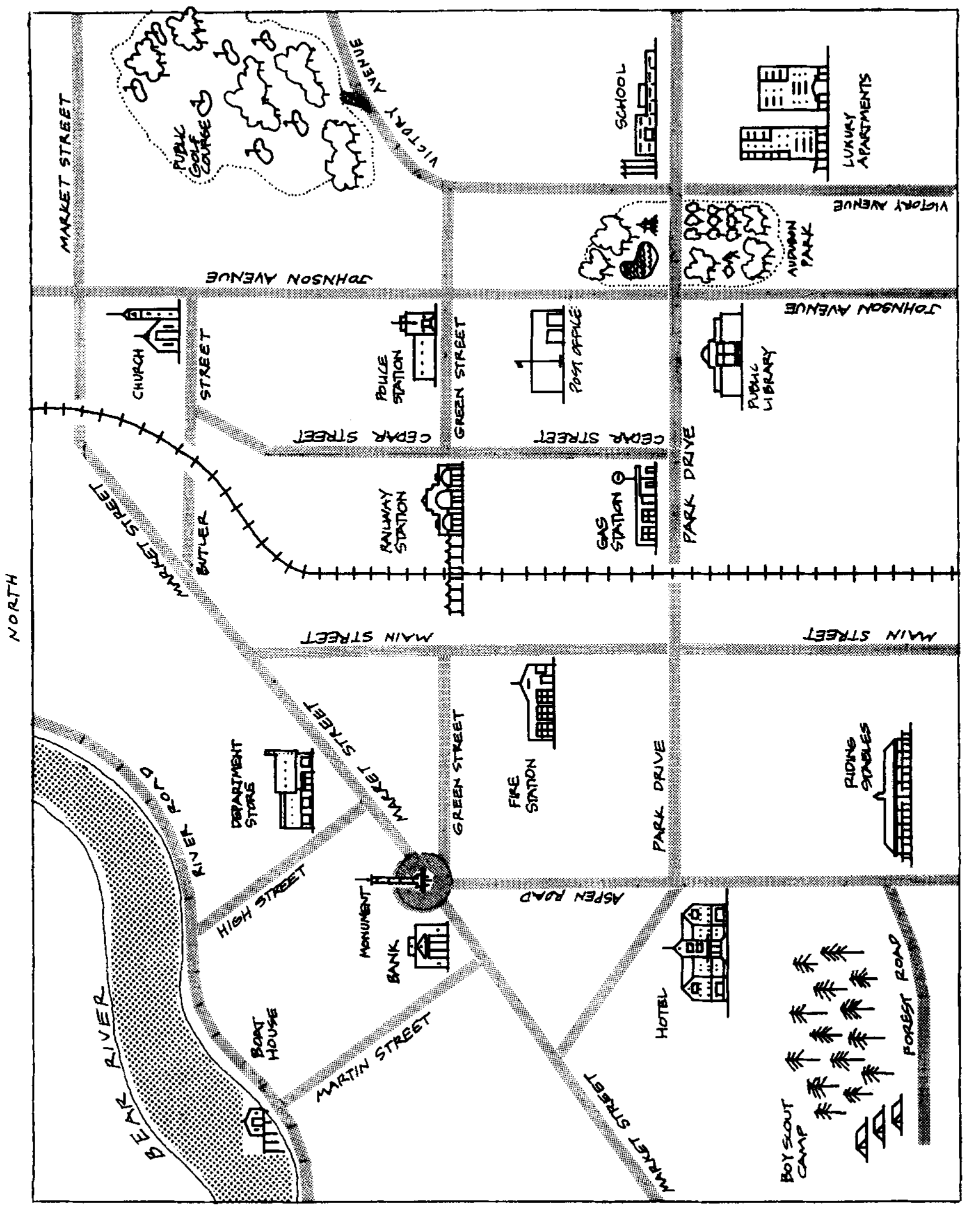

FIG. 1. Town Map.

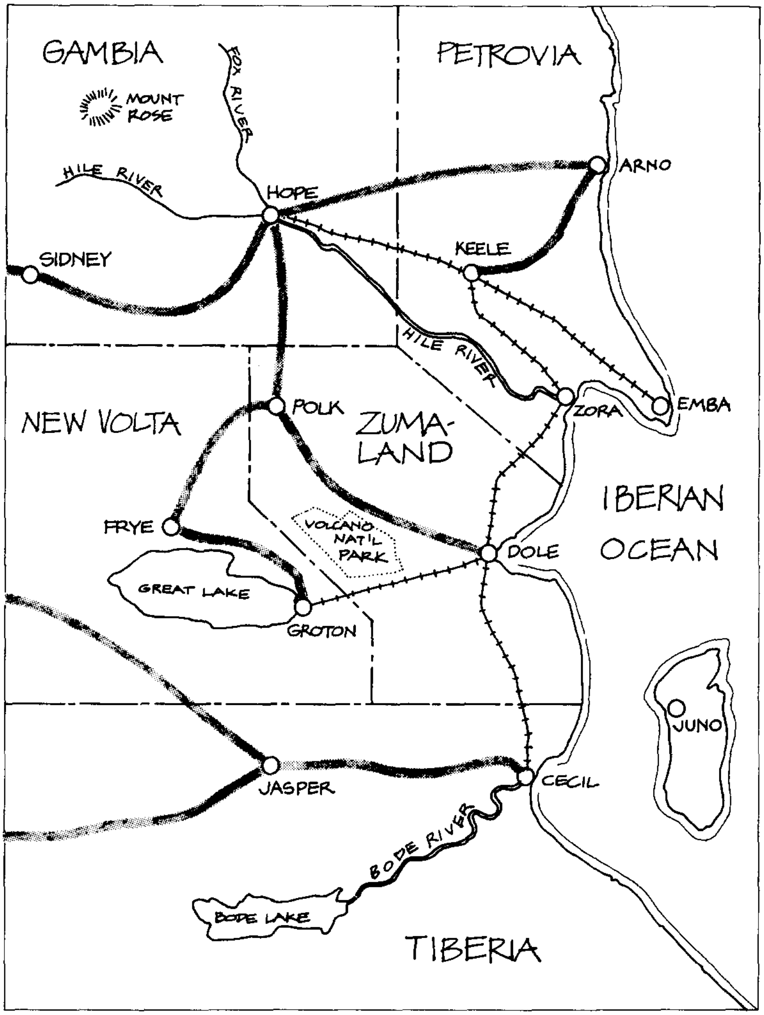

FIG. 2. Countries Map.

performing. A practice trial on a different map familiarized each subject with the study–recall procedure and protocol procedure. The subject then studied a copy of either the Town Map or the Countries Map for 2 min. During that time the experimenter tape recorded the subject's verbal protocol. After the study period, the experimenter removed the map and the subject attempted to draw, using pencil and paper, as much of the map as he or she could remember. Unlimited drawing time was provided. The experimenter then removed the reproduced map and gave the subject the correct map to study for 2 more min. After six such study–recall trials (or fewer, if the subject had learned the map perfectly), the subject solved six route-finding and spatial judgment problems. These problems required recall and integration of route and location information from the map. For example, one such problem for the Town Map required subjects to specify the route they would take and buildings they would pass in traveling from the Luxury Apartments to the gas station and then on to the bank. Solutions to these problems were tape recorded. The study–recall procedure was then repeated for the second map. Order of map presentation was counterbalanced across subjects.

Results and Discussion

Map Reproduction

For scoring subjects' maps, units of information called "elements" were defined. An element is a map symbol representing a physical or conceptual entity, such as a building, road, country, lake, or park. Each element could have two attributes: spatial location and a verbal label. The location of a point element was defined relative to the adjacent landmarks (e.g., a building located at the intersection of two streets). The spatial attributes of a one- or two-dimensional element (e.g., a street or country) included its shape and location with respect to adjacent elements. The Town Map contained 33 elements, 32 of which were named. The Countries Map contained 43 elements, 26 of which had names.

Recall of spatial and verbal information was scored independently. A labeled element could be recalled with either correct spatial placement, correct labeling, or both. Unlabeled elements were scored only for correct spatial placement.

The following decision rules were adopted for scoring maps: (1) verbal labels of elements had to be correctly recalled with the exception of "Street," "Drive," or "Avenue" designations; (2) spatial placements had to preserve the correct interrelationships among the immediately adjacent elements (e.g., on the Countries Map, Volcano National Park had to be located south of the Polk–Dole highway and north of the Groton–Dole railroad); (3) major shape characteristics were required for correct spatial placement (e.g., the coastline on the Countries Map included three bays and a peninsula), but minor shape details were not required of the reproductions (e.g., road and railroad segments on the Countries Map could be drawn as straight lines).

For each subject, the proportions of verbal attributes, spatial attributes, and entire elements correctly recalled at each trial were calculated separately for each map. As expected, recall increased over trials for every subject. Final trial recall is indicative of the individual variation in performance. Table 1 shows the percentage of verbal attributes, spatial attributes, and complete elements correctly recalled on the last trial for each map. The subjects are rank-ordered from left to right according to their mean performance across maps. The sex of each subject is indicated in parentheses.

Performance ranged from 100% correct on the reproduced map after five trials (Subject DW) to 19% correct after six trials (Subject NN).

TABLE 1

Percentage of Map Information Recalled Correctly on Final Trial and Percentage of Navigation Problems Correctly Solved[a]

	Subject							
	DW(M)	JM(F)	BW(M)	MS(M)	BB(F)	FK(M)	CD(F)	NN(M)
Countries Map								
Complete map elements	100	95	91	72	53	79	37	19
Verbal attributes	100	100	100	100	65	77	73	50
Spatial attributes	100	95	91	72	58	93	46	28
Navigation problems	100	100	67	83	17	33	33	0
Town Map								
Complete map elements	94	94	97	82	79	48	76	39
Verbal attributes	100	100	100	100	100	81	97	75
Spatial attributes	94	94	97	82	79	64	79	45
Navigation problems	100	100	83	83	67	50	0	0

[a] Trial 5 for Subject DW on the Countries Map; Trial 4 for DW on the Town Map; Trial 6 for all other subjects.

Subjects' performance was consistent across the two maps and was significantly correlated, $\rho = .78$, $p < .05$. Subjects typically had learned more of the verbal information (88%) than spatial information (77%) by the final trial. However, subjects' recall of spatial and verbal attributes was significantly correlated, $\rho = .74$, $p < .05$. Recall from the Countries Map was used to compare learning of labeled and unlabeled elements. Across all learning trials, subjects recalled spatial information associated with labeled elements (55%) better than the spatial information from unlabeled elements (42%), $t(7) = 2.77$, $p < .02$. This result is consistent with other experiments that show superior memory for labeled over unlabeled spatial information (Pezdek & Evans, 1979).

Problem Solving

The use of subjects' map reproductions as a measure of learning has two potential problems. First, subjects might have been able to draw the map on an immediate test but not be able to solve complex problems requiring simultaneous retrieval and integration of several map elements. Second, some subjects might lack the skills necessary to draw the map even though they had actually learned the information. Therefore, we used performance on the six navigation problems for each map to test the reliability of the recall scores. Table 1 displays these data. While problem solving required processes in addition to simple retrieval of knowledge, performance should correlate with the learning data. As expected, subjects' problem-solving performance was highly correlated with last trial recall, $r = .90$, $p < .001$.

Verbal Protocols

We analyzed the verbal protocols separately from the map reproductions. For each study trial, the second author scored a subject's protocol to determine the set and sequence of procedures employed to learn the map. The protocol was first segmented into sections such that each individual section mentioned a property of a particular map element, a relationship between two or more elements, an intention to perform a certain action, or a comment on the study process itself. (Figure 3 demonstrates this segmentation for one protocol). Each section was then evaluated to determine which, if any, high-level procedure it represented.

We had identified and operationalized the set of possible procedures prior to the experiment by analyzing the learning protocols of eight pilot subjects. We thus applied specific decision rules in scoring the sections of the protocols. (These criteria are discussed in the description of the individual procedures below.) When ambiguous cases arose, we discussed the scoring options until we reached a consensus, and we then attempted to refine the decision criteria.

We established the reliability of the scoring decisions in two ways.

1 Um. First I notice that there's a railroad that goes up through the middle of the map.

2 And then, the next thing I notice is there's a river on the top left corner, and let's see.

3 There's a main street and . . . I guess I'd try and get the main streets first.

4 That would be Market and Johnson and Main. Try to get the relationship of those.

5 On these two streets, they both start with an M.

6 Then I'd just try to get down the other main streets, that, uh,

7 Victory Avenue comes below the golf course, and

8 then goes straight down and

9 becomes parallel with Johnson, and . . .

10 I guess I'd try to learn the streets that are parallel first, parallel to each other.

11 Just try to remember which, in which order they come.

12 I guess with this one I could, since there's a sort of like a forest, I could remember that this is Aspen, and um,

13 let's see, and Victory, I guess I could relate it to the golf [course], winning the golf [match].

FIG. 3. Verbal protocol from a study trial on the Town Map.

First, the scorer analyzed a sample of the protocols twice to assess intra-rater reliability. In addition, a second scorer analyzed several randomly selected protocols. In both cases, the correlation between the two sets of decisions was better than .90.

Figure 3 presents a protocol taken from one subject, CD, on the first trial on the Town Map. This protocol illustrates several of the learning procedures we observed repeatedly in subjects' study behavior. In sections 1 and 2 of the protocol, CD notices large, salient features of the map. In section 3 CD decides to restrict her attention to a subset of the map elements (the streets) and to ignore the other elements. In section 10 she refines this decision to include only the parallel north–south streets. With this constraint, CD samples individual streets and uses other procedures to learn their names and locations. In section 5 she uses the first letter "M" of two intersecting streets, Main and Market, as a mnemonic to remember their names. In sections 7 and 8 CD details the shape of an irregular street, Victory, and in section 9 she notices an implicit spatial relationship (parallelism) between the street and Johnson Avenue. Finally, in sections 12 and 13 CD produces associative elaborations, using other semantic knowledge, to relate two street names to adjacent elements.

In the analysis of this and the other learning protocols, we identified four general types of processes subjects employed during study: *attention, encoding, evaluation, and control.* We found direct evidence for the first three types in subjects' protocols. Evidence for control processes was inferred from subjects' behavior but not observed directly in the protocols. Each of these process categories comprises several individual processes that are components in the high-level process. The first two columns of Table 2 summarize the four categories of processes and the subprocesses within each category. The last column summarizes the procedures observed in the protocols that correspond to these presumed subprocesses.

The first type of process listed in Table 2 includes the attentional processes required for perception of the physical map. Posner and Boies (1971) distinguished three components of attention: general arousal, restriction of attention to task-relevant cues, and switching of attention between tasks. This distinction is useful in understanding the attentional demands on subjects who are perceptually sampling information from the map. In our paradigm subjects have only one task (to study the map), but they have a variety of perceptual features to which they might attend. General arousal is presumably a background process that determines whether or not and how vigilantly the subject fixates on the map. Focus of attention refers to the process by which subjects restrict eye fixations to a particular subset of the information on the map. Attention switching refers to the process by which subjects shift their focus of attention to a new location on the map.

We directly observed two types of attentional procedures. The first of these *partitioning,* was a technique for restricting attention to a subset of the map information. Since a map contained more information than subjects could learn on a single trial, they frequently decided on early learning trials to attend selectively to a well-defined portion of the map. Subjects might thus partition the map by (a) spatial region (e.g., by attending only to elements in the northwest corner) or (b) by conceptual category (e.g., by attending only to the streets on the map). Sections 3 and 10 of the protocol given in Fig. 3 illustrate a subject's use of the second partitioning procedure. In general, sections of protocols were scored as illustrative of this procedure whenever subjects stated an intention to study only a particular subset of the map elements.

The second type of attentional procedure comprised sampling proce-

TABLE 2

Processes in Learning and Corresponding Procedures from the Protocols

Type of process	Subprocess	Procedure
Attentional		
	General arousal	
	Focus of attention	Partitioning
	Attention switching	Sampling
		Random
		Stochastic
		Systematic
		Memory directed
Encoding		
	Maintenance	Rehearsal
	Elaboration	Verbal learning
		Association
		Mnemonics
		Counting
		Spatial learning
		Imagery
		Labeling
		Pattern encoding
		Relation encoding
		Schema application
Evaluation		Evaluation
	Retrieval	
	Comparison	
Control	Procedure selection	
	Procedure switching	

dures. Sampling procedures determined the sequence of shifts in a subject's focus of attention among map elements. Subjects exhibited four types of sampling procedures. *Systematic sampling* involved shifting attentional focus according to a subject-defined decision rule or criterion (e.g., studying elements from west to east or from the outside of the map in). *Stochastic sampling* involved shifting the focus of attention from the current element to an adjacent element, but in no systematic or consistent direction. The sequence of foci seemed to describe a "random walk" (Feller, 1966) through the map. In *random sampling* the focus of attention shifted haphazardly around the map, with the new focus seemingly independent of the previous focus in both location and content. These three sampling procedures could be invoked on any learning trial. The scorer identified these procedures in the protocols by noting the sequence of elements in the subjects' reported focus of attention. This sequence usually corresponded clearly to one of the three sampling types. (For example, the protocol in Fig. 3 illustrates random sampling.) In addition, subjects employing systematic sampling typically stated explicitly their intended sequence of foci. Subjects generally exhibited only one of these three procedures per trial. However, occasionally subjects would switch techniques within a trial. Such a switch was indicated in protocols by either an explicit statement of intention or by an obvious shift in the relationship between the relative locations of successive foci.

The fourth procedure, *memory-directed sampling,* could occur on any trial after the first. This procedure occurred when a subject decided to study particular elements that had not yet been learned. For example, at the beginning of a new study trial, a subject might decide to study the location of a river because s/he could not remember it on the previous recall trial. The scorer identified this procedure in the protocols from statements indicating an inability to recall particular elements, intention to study these elements, and subsequent evidence of focus on them. Following study of these elements, the subject would shift to one of the other three sampling procedures.

When information was in a subject's focus of attention, various encoding procedures were required to maintain it in working memory, encode and elaborate it in long-term memory, and integrate it with other learned information. These procedures may be categorized according to the type of information encoded. Verbal learning procedures operated primarily on semantic and linguistic information, such as the names of buildings or roads. Spatial learning procedures operated primarily on element shape and location information. Subjects could maintain both types of information in working memory by actively rehearsing a set of names or location descriptions. The identification criterion for the *rehearsal* procedure required the juxtaposed repetition in the protocol of a set of element names. The repetition of each element name constituted an instance of rehearsal.

Three verbal learning procedures were observed. *Counting* helped subjects to cluster several elements sharing a particular property. This procedure was indicated whenever a subject enumerated the elements sharing a particular property (e.g., "there are five cities on the Iberian coast"). Subjects used *mnemonics* to generate memorable retrieval cues for a set of names, such as "SHA," the northernmost cities on the Countries Map: Sidney, Hope, and Arno. In section 5 of the protocol given in Fig. 3, CD uses the letter "M" as a mnemonic for retrieval of the names of two main streets, Main and Market. This technique was indicated whenever a subject labeled a set of elements using the first letter of their names. The *association* procedure involved the elaboration of verbal attributes by association to or embellishment with some related prior knowledge. For example, several subjects noted that Market Street on the Town Map was similar to Market Street in San Francisco in that it formed an oblique angle with intersecting streets. The scorer identified this type of association from statements that indicated similarities between map elements and familiar real-world names or locations. Other associations related two or more elements from the map itself using world knowledge. In sections 12 and 13 of the protocol, CD associated Aspen Road with the neighboring forest, and Victory Avenue with the adjacent golf course through the association "Victory at golf." The scorer identified a statement illustrative of this type of association if it satisfied one of three criteria. The statement could supply a category name that subsumed a set of elements, it could name or suggest semantic relationship between several map elements (as in section 12), or it could supply an action or narrative that associated adjacent elements.

Similarly, we observed four procedures for encoding spatial attributes. Some subjects used *visual imagery* to memorize configurations of spatial information. During study these subjects closed their eyes and attempted to draw shapes or name elements in a mental image, reported attempts to form a mental picture of the map, and focused their attention exclusively on line shapes. This procedure was indicated by subjects' reports of attempts to construct mental images or pictures. *Labeling* involved the generation of a verbal cue for recall of a complex spatial configuration. For example, a subject might notice that the northern five roads on the Countries Map formed a figure of a stick man running to the west, or that the coastline formed the profile of a face. The scorer judged a protocol to contain this procedure whenever a subject used the name of a concrete object to refer to a shape or spatial configuration on the map. In *pattern encoding* a subject would notice a particular shape or spatial pattern of a single element, such as a street that curved to the east. In section 8 of the protocol shown in Fig. 3, CD uses this procedure to specify the shape of Victory Avenue. A statement was scored as exemplary of this procedure whenever a reference was made to the specific shape of an element. Finally, the *relation encoding* procedure refers to the verbalization of a spatial relationship between two or three elements. For example, CD states in Fig. 3 that Victory Avenue is "below the golf course" and is "parallel to Johnson." We identified 15 relational predicates of two arguments (e.g., below, next to, east of, at) and two predicates of three arguments (e.g., between, connects). The arguments to these predicates could be either element names, a location defined by the intersection of two roads or railroads, or the entire map itself (as in section 1 of Fig. 3). Any statement that could be represented as 1 of these 17 relationals was scored as illustrating the relation encoding procedure.

One encoding technique, *schema application*, was used by some subjects to learn either spatial or verbal information. This procedure involved encoding information by association with a preexisting, prototypical configuration of such information. For example, one might learn the spatial configuration of streets on the Town Map by initially supposing a prototypical rectilinear grid and then learning particular deviations from that grid. Statements in which subjects indicated that they were learning some aspect of the map with respect to a prototype or typical configuration of that information were scored as illustrative of this procedure.

The third type of process evident in the protocols was *evaluation*. Subjects would monitor their learning progress by considering what they had already learned and what they still needed to study. In particular, subjects evaluated elements in the current focus of attention to determine whether or not they had learned them well enough to recall them later. Any statement indicating that the subject did or did not yet know particular elements or categories of elements was representative of this procedure. This evaluation required a search for and retrieval of the memory representation of information from memory, a comparison of the representation to the same information on the map, and a decision about whether the two were equivalent. When subjects decided they had not learned the information, they might then study the element using one of the encoding procedures.

Finally, we assume there is a set of control processes that directs the overall flow of processing in the learner. In particular, the control processes must include at least a mechanism for selecting from a set of available processes those to be activated (procedure selection) and a mechanism for deciding when to terminate a procedure and switch to a new one (procedure switching). Subjects rarely articulated specific procedures or criteria for selecting among available techniques. However, as discussed below, we did observe differences among subjects in the control of procedure activation.

Analysis of Individual Differences

To understand the relationship between study procedures and learning performance, we contrasted the protocols of good and poor learners. While subjects' performance across the two maps was highly reliable, their learning procedures varied across the two maps. Across subjects, the number of occurrences of a procedure on one map was significantly correlated with the number of occurrences of the same procedure on the other map for only 5 of the 15 procedures. On initial inspection, it appeared that differences in procedure profiles between maps were as pronounced as differences in profiles between subjects. Therefore, in comparing performance and procedure usage, we treated each subject–map pairing as independent. Thus, 16 sets of observations (each of eight subjects learning each of two maps) entered into the analysis of performance.[2]

We defined good learners as subjects who recalled at least 90% of the map elements correctly by the last trial. This criterion distinguished 6 good protocols (three subjects on each of two maps) from 10 poor protocols (five subjects on each map). Mean final trial performance was 95% for the good learners and 58% for the poor learners.

Using this criterion, several reliable processing differences between good and poor learners emerged. These data appear in Table 3. The first three rows of the table show that good learners were superior to poor learners in the mean percentage of complete elements, spatial attributes, and verbal attributes recalled on each trial. The second part of the table presents the mean number of occurrences of each procedure across the six study trials in each learner's protocols. The numbers in brackets indicate the range in the number of occurrences across the 16 sets of protocols. The numbers in parentheses indicate the proportion of cases (out of 6 or 10) in which the procedure occurred. Mann–Whitney U tests were used to evaluate the reliability of the differences in frequency of procedure usage. Overall, there was no reliable difference between the mean length of a good learner's protocol (186 words) and a poor learner's protocol (175 words). Furthermore, there was no difference between good and poor learners in the mean number of *different* procedures used (10.5 versus 10.1). However, as Table 3 shows, good and poor learners did differ in which procedures they used and how frequently they used them. The major differences in each category of processes are summarized below.

Attention. Good learners adopted a more systematic approach to learning than poor learners. As Table 3 shows, good learners used the partitioning procedure, stochastic sampling, and systematic sampling more frequently than poor learners, although only the last of these differences was reliable. These differences can be best understood in terms of the "divide-and-conquer strategy" that utilized combinations of these procedures. A subject adopting this strategy would define a subset of the map information using the partitioning procedure, and then systematically focus on elements in that subset (using stochastic or systematic sampling)

[2] We computed correlations between procedures and performance using a weighted least-squares procedure (Draper & Smith, 1968) to test the hypothesis that variance in performance scores derived from subject as well as error components. Likelihood ratio tests indicated that assuming subject variance to be zero provided as good a fit to the data as assuming any non-zero value. Furthermore, correlations computed using non-zero estimates of the subject variance did not differ substantially from those produced assuming no subject variance component. Therefore, the treatment of subject–map pairs as independent appears to be justified.

TABLE 3

Mean Performance and Procedure Usage for Good and Poor Learners in Experiment 1

Variable	Range	Good learners (N = 6)		Poor learners (N = 10)	
Mean percentage recall per trial					
Complete elements		63.67**		35.50	
Spatial attributes		71.33**		42.40	
Verbal attributes		73.00*		53.90	
Mean use of procedure per protocol and proportion of protocols in which procedure occurred (in parentheses)					
Attention					
Partitioning	[0–3]	2.33	(.83)	1.50	(.70)
Random sampling	[0–2]	0.00*	(0)	1.10	(.60)
Stochastic sampling	[0–4]	1.33	(.67)	1.00	(.60)
Systematic sampling	[0–6]	2.17*	(1.00)	0.90	(.70)
Memory-directed sampling	[2–21]	10.17*	(1.00)	6.20	(1.00)
Encoding					
Schema application	[0–3]	0.00	(0)	0.60	(.30)
Rehearsal	[0–195]	57.33*	(.83)	5.70	(.70)
Association	[0–17]	5.00	(.83)	4.90	(1.00)
Mnemonics	[0–2]	0.00	(0)	0.40	(.30)
Counting	[0–11]	6.17*	(1.00)	2.40	(.70)
Imagery	[0–6]	2.67*	(.67)	0.20	(.20)
Spatial labeling	[0–7]	2.67	(.67)	1.10	(.40)
Pattern encoding	[0–19]	8.33*	(1.00)	2.50	(.90)
Relation encoding	[12–54]	39.00*	(1.00)	17.10	(1.00)
Evaluation					
Evaluation	[4–16]	11.17	(1.00)	10.60	(1.00)
Evaluation of unlearned elements (%)		81.50*		61.50	
Evaluation accuracy (%)		97.17*		81.90	
Study unlearned elements (%)		95.17*		75.20	

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

until all elements in the set had been considered. This strategy was particularly advantageous on early learning trials, when subjects had not yet learned the majority of the map information. This strategy of combining partitioning and structured sampling appeared in 83% (5 out of 6) of the sets of good learners' protocols. In contrast, it appeared in only 10% (1 out of 10) of the protocols of poor learners. Three of the poor learners' protocols did not contain the partitioning procedure. In the remaining 6 protocols containing the partitioning procedure, subjects either (a) adopted inconsistent or unsystematic sampling procedures (e.g., random sampling) to accompany partitioning (6 protocols), (b) failed to restrict their attention to elements in the partitioned set (2 protocols), and/or (c) abandoned consideration of elements in the partitioned subset before all elements in the set had been considered (2 protocols). This last case occurred when subjects could find no procedure for encoding the sampled information.

On later trials, when subjects had learned the basic framework of the map, good learners relied heavily on memory-directed sampling to determine their focus of attention. That is, good learners knew which elements were as yet unlearned and searched for and focused on that information. Their technique for selecting attentional focus was thus goal directed. As Table 3 shows, good learners used this procedure significantly more frequently than poor learners. Poor learners typically used this sampling procedure to find one or two unlearned details but then switched to a stochastic or random sampling procedure.

Encoding. Subjects differed very little in their use of verbal learning procedures. However, effective learners used frequent and varied spatial learning procedures, while poor learners did not. Two of the three good learners reported constructing in memory and rehearsing a visual image of both maps. The use of imagery frequently entailed rehearsing a set of recently perceived elements. The high correlation ($r = .86$) between the frequency of imagery and rehearsal accounts for the fact that good learners used rehearsal more often than poor learners. Good learners elaborated and refined their knowledge of spatial location by noticing and encoding explicit shapes (pattern encoding) or spatial relations (relation encoding) among two or more map elements. Poor learners used these procedures significantly less frequently than good learners, as shown in Table 3. Poor learners frequently reported that they could think of no procedure for learning the spatial information, and, in general, their repertoire of spatial learning techniques was more limited than that of good learners.

Evaluation. All learners extensively evaluated their learning progress during study. However, two characteristics of the evaluation procedure distinguished good learners from poor learners. Those differences are shown in the last three rows of Table 3. First, good learners evaluated primarily unlearned elements (81.5% of all evaluation statements), ignoring consideration of information already learned. Poor learners evaluated a significantly smaller proportion of unlearned elements, and instead spent study time confirming that they knew certain information. This is surprising in light of the fact that poor learners, by definition, knew less than good learners, and hence their a priori probability of selecting an unlearned element to evaluate was higher than for good learners. However, as noted above, good learners' study behavior was goal directed. They would bring to each study trial knowledge of what information they had not yet learned, find that information on the map, and then study it using an appropriate elaboration procedure. Poor learners seemed more data driven: they would first focus on a randomly selected map element, and then evaluate the element in memory to decide whether or not it had been learned.

Second, when subjects assessed whether or not they knew an element, they could be either correct or incorrect in the evaluation. We determined the accuracy of subjects' evaluations by comparing their statements to the accuracy of the map reproductions on the previous trials. As Table 3 shows, good learners were significantly more accurate in their evaluations (97% correct) than poor learners (82%). That is, good learners were superior at assessing their current state of learning and "knowing what they know." Such knowledge about the state of memory has been referred to as metamemory, and its development has been extensively studied in children (Brown, 1975, 1978; Flavell & Wellman, 1977). Although this phenomenon has been little studied in adults, it may represent an important source of systematic individual differences in learning and memory tasks.

Control. When good learners adopted a particular heuristic, they would continue to use it until it had achieved its purpose. For example, when good learners used partitioning, they would sample only information in the partitioned set until all elements had been considered. In contrast, poor learners frequently abandoned this heuristic abruptly and prematurely. This typically occurred when subjects could think of no heuristic for learning the sampled information.

Poor learners also failed to effectively select and use heuristics following evaluations. When good learners decided that they had not yet learned an element, they immediately studied it. As the last row in Table 3 shows, the conditional probability of a good learner immediately studying an element given that a negative or "unlearned" decision had been made about it was .95. For poor learners, this conditional probability (.75) was significantly lower. After making a negative evaluation, these subjects might shift attention to a new element without studying the unlearned information.

Performance of Experienced Map Users

Because three subjects were highly experienced at viewing and using maps, we expected that they would also be the best learners. However, the experienced users' performance was not uniform. DW was the best learner, with a mean across maps of 97% correct recall on the last trial, FK ranked sixth out of eight subjects, with mean last-trial performance of 63.5%, and NN was the worst learner with a mean last-trial performance of 28.5%. This variability suggests that subject differences cannot be ex-

TABLE 4

Frequency of Procedure Usage by Experienced Map Users

Procedure	Subjects			Mean across all 8 subjects
	DW[a]	FK[b]	NN[b]	
Partitioning	6	4	0	3.62
Imagery	5	0	0	2.12
Pattern encoding	9	4	2	9.38
Relation encoding	32	27	39	50.62
Schema application	0	1	5	0.75
Association	1	7	21	9.87

[a] Based on 9 trials across the two maps.
[b] Based on 12 trials across the two maps.

plained by differential familiarities with the material or task. If familiarity with maps were the critical variable, then all experienced users should have performed well.

Instead, differences among experienced users seemed to be due to differences in their study procedures. The major differences are summarized in Table 4 as the frequency of usage (across both maps) of certain procedures. The last column of Table 4 shows the mean across all eight subjects for each of these procedures.

The procedural choices of experienced users matched their self-reported aptitudes for learning. The best learner, DW, stated that he had good visual memory and frequently constructed visual images to learn and remember information. On six of his nine study trials, he used the partitioning procedure to identify subsets of the spatial information (e.g., the roads), and then used imagery to encode that information. Because he was able to use these procedures effectively, he had no difficulty learning the spatial information on the maps. Thus, while DW used partitioning and imagery more frequently than the average subject, he actually used the other spatial learning procedures *less* frequently.

On the other hand, NN, the worst learner, reported that he had very poor memory for spatial information, and had never experienced having mental images. NN used primarily verbal learning procedures and the one spatial learning procedure that entailed linguistic encoding of spatial relations (relation encoding). NN also attempted to learn object locations and relationships by relying on his prior knowledge of common geographical configurations (e.g., noticing that a park was across the street from a school). This strategy led to the frequent use of the association and schema application procedures. Because the geographic information on the maps was fictitious (although not anomalous), this strategy was unreliable for learning much of the spatial information. He reported that he found the learning task to be extremely difficult and did not attempt to learn some of the more complex spatial configurations of information, such as the shapes of the coastline and railroads on the Countries Map.

The third experienced map user, FK, was variable in his learning performance. On both maps FK ranked low on recall of verbal information. On the other hand, FK had little difficulty learning most of the spatial information. On the Countries Map, FK studied the spatial information using partitioning and relation encoding and was as successful as the best learners. On the Town Map, he rapidly learned building and landmark locations using the same procedures, but he avoided learning the detailed shapes and locations of the streets because he could not learn their names. FK was the only subject with better overall recall of spatial attributes than verbal attributes. This reversal may perhaps be explained by FK's professional experiences with maps. As an Air Force pilot, he frequently learned spatial information from maps for later location and identification from the air. For a pilot performing target acquisition and reconnaissance, learning the spatial locations and interrelationships of terrain features is more important than learning names. As FK explained, ". . . when you're flying, you don't really care if that mountain is Mont Blanc or Mount something-or-other as long as it's where it's supposed to be in relation to everything else." Since name learning was unimportant in FK's past map-learning experience, he did not have (and could not think of) any useful procedures for encoding them.

Although we have demonstrated consistent differences in the learning procedures used by good and poor learners, such procedures are but one of several potential sources of individual differences on this task. It is not clear what role the use of these techniques alone plays in learning. While some studies have shown that learning can be improved through the use of such techniques as imagery (Marks, 1973; Paivio, 1971; Rohwer, 1973) or chunking (Bower & Winsenz, 1969; Belmont & Butterfield, 1971; Hunt & Love, 1972; Estes, 1974), other studies have demonstrated that individual differences remain even when subjects cannot use such procedures (Huttenlocher & Burke, 1976; Lyon, 1977).

Hunt (1978) has proposed that individual differences in cognition arise from three sources: differences in the use of simple processing procedures, differences in knowledge related to or about the task, and differences in the ability to perform the low-level mechanics of information processing. Differences in subjects' profiles of procedure use clearly differentiated good from poor learners in Experiment 1. On the other hand, the failure of experienced map users to perform consistently better than novice map users suggests that domain knowledge did not contribute to performance differences. The third source of variation, the mechanics of information processing, refers to differences in subjects' ability to carry out basic operations on the physical representation of a symbol. Such operations include decoding, visualization, selective filtering, memory retrieval, and memory comparison.

Clearly, differences at this level of processing can influence high-level procedure and strategy choices (e.g., MacLeod, Hunt, & Mathews, 1978). Our analysis of experienced map users' performance revealed that subjects who differed in self-reported visualization ability employed different procedures for learning spatial information. Since the acquisition of spatial information was a salient difference between good and poor learners, it is reasonable to postulate that subjects also differed in their visual or spatial ability. Therefore, differences in basic ability may have produced the observed differences in both performance and procedure selection. If this were the case, then the use of certain procedures would correlate with, but not cause, performance differences.

EXPERIMENT 2

Experiment 2 tested directly the efficacy of certain procedures for learning. This experiment investigated whether subjects trained to use learning procedures correlated with success in Experiment 1 would perform better than subjects of equivalent ability using self-selected procedures. The set of "effective" techniques comprised three procedures for learning spatial information (imagery, pattern encoding, relation encoding), two procedures for using self-generated feedback to guide subsequent study behaviors (memory-directed sampling, evaluation), and a procedure for dividing the learning problem into subproblems (partitioning).

To contrast training in the use of effective procedures with the effects of instruction per se, we included in Experiment 2 subjects who received training on six procedures uncorrelated with performance in Experiment 1. These procedures included mnemonics, spatial labeling, rehearsal, and three association procedures. The first association procedure required the creation of a link between some map information and some related prior knowledge. For example, the subject might notice that Market Street on the Town Map is spatially similar to Market Street in San Francisco. A second type of association related two or more objects from the map using some additional world knowledge. For example, one might link Victory Avenue with the adjacent golf course through the association "Victory at golf." A third use of this general technique required the creation of a narrative or scenario incorporating several map elements (e.g., "The BUTLER went to CHURCH and saw CEDAR trees in the PARK."). Since all six of these procedures were uncorrelated with success in Experiment 1, training subjects to use them should not affect their performance.

We also assessed the visual memory ability of subjects using the Building Memory test from the *Kit of factor-referenced cognitive tests* (Ekstrom, French, & Harmon, Note 1). This test measures subjects' ability to remember the configuration, location, and orientation of spatial information in a complex display. If visual memory accounts for much of the variation in learning, or if it is a prerequisite for using high-level procedures, then training should have little effect on performance.

Method

Materials

We used three maps as learning materials. The Town Map (shown in Fig. 1) served as the pretraining stimulus, and the Countries Map (shown in Fig. 2) served as the post-training stimulus. A third map adapted from a study by Shimron (Note 2) was used by subjects during training to practice their learning procedures. This map depicted an imaginary county, containing roads, cities, a river, and mountains.

Subjects

Forty-three subjects participated in the study. Thirteen were Santa Monica Community College students who were paid $3.50 per hour. Thirty subjects were UCLA undergraduates who participated in order to fulfill a course requirement.

Design

Subjects were randomly assigned to either the control group or to one of two training groups. The Effective Procedures group ($n = 14$) received instruction on six procedures correlated with successful learning in Experiment 1. These procedures were partitioning, imagery, pattern encoding, relation encoding, memory-directed sampling, and evaluation. The Neutral Procedures group ($n = 16$) received instruction on six procedures that were previously uncorrelated with performance: mnemonics, spatial labeling, rehearsal, and three association procedures. The No Procedures group ($n = 13$) received no training.

Procedure

Within each treatment condition subjects were tested in groups. They were told that the study investigated the effectiveness of certain procedures for learning maps and that their task was to learn, using any techniques they knew, the map they would be shown. Each subject was then given a copy of the Town Map to study. After 2 min the map was withdrawn and subjects were instructed to draw as much of the map as they could remember. Recall time was limited to 7 min. Three study–recall trials, administered in this manner, served as a pretest of map learning.

Following these trials, each group received different instruction on the use of learning techniques. For the Neutral and Effective Procedures groups, the experimenter described each of the respective procedures for that group in detail. Instructions for the use of the evaluation procedure emphasized, in addition to the technique itself, the advantages of accuracy, attention to unlearned elements, and subsequent study of those elements. The experimenter illustrated the use of each procedure with examples on the Town Map. Subjects studied these examples on their own copies of the map.

Subjects in the No Procedures group were instructed to continue using their own learning techniques on the next maps. In addition, the experimenter provided some general suggestions for improving performance on subsequent maps. She urged subjects (a) to concentrate on the task and not to be distracted, (b) to evaluate the effectiveness of the techniques they were using, (c) to discontinue using any techniques that appeared to be ineffective, and (d) to try to learn as much as possible in the time provided. For all three groups, this training session lasted between 20 and 30 min.

Subjects were then given copies of the County Map and instructed to practice the techniques that they had been taught. Two trials, consisting of 2 min of study and 5 min for recall, were provided. Following these practice trails, the experimenter reviewed the learning procedures and answered any questions about their use. Subjects were then given copies of the Countries Map and instructed to use the techniques they had been taught whenever possible. Subjects alternately studied and reproduced the map on five study–recall trials. Two minutes were provided for each study trial, 7 min for recall.

After the last recall trial, subjects completed two questionnaires reporting the procedures they used during study. Each questionnaire comprised 16 questions, each of which required subjects to indicate the frequency with which they used a particular procedure. Nine of the sixteen questions referred to the effective learning procedures, and six questions referred to the neutral procedures. One question referred to a procedure not in either set. For each question, a statement describing the procedure was followed by an example of its use on the appropriate map. Subjects rated how often they used the procedure on a scale ranging from "0" (never used the procedure) to "6" (used procedure on every trial). Subjects consulted their maps while answering all questions. Following completion of the questionnaire, subjects took the psychometric test of visual memory ability.

Results and Discussion

For each subject, the proportions of verbal attributes, spatial attributes, and entire elements correctly recalled were computed for each trial. An overall score for each map was obtained by computing the mean across recall trials. Scores for the Town Map represent the mean recall across three learning trials; scores on the Countries Map represent recall across five trials.

Pretraining Procedure Usage

As in Experiment 1, we were interested in the relationship between procedure usage and learning performance before training. Therefore, we divided the 43 subjects into good and poor learners based on performance on the first map. We defined good learners as subjects whose last trial recall was at least 45% and whose mean recall across trials was at least 34%. Poor learners all had last trial performance of less than 40% and mean recall of less than 32%. These criteria produced a group of 20 good learners and a group of 20 poor learners. Three subjects who could not be unambiguously classified were discarded from this analysis.

Table 5 contrasts these groups on reported usage of the 12 procedures trained in Experiment 2. Differences between groups were evaluated using one-tailed t tests. As the first three rows of Table 5 show, good learners were superior in recall of complete elements, spatial attributes, and verbal attributes. These learners also tended toward more frequent use of the "effective" procedures. As in Experiment 1, good and poor learners did not differ in their frequency of use of the evaluation procedure. However, good learners used four of the other five Effective Procedures significantly more often than poor learners. In contrast, good and

TABLE 5

Comparison of Pretraining Performance and Procedure Usage for Good and Poor Learners in Experiment 2

Variable	Good learners (N = 20)	Poor learners (N = 20)
Mean percentage recall per trial		
Complete elements	45.05**	20.20
Spatial attributes	48.20**	26.10
Verbal attributes	74.30**	52.15
Mean frequency rating of procedure usage		
Effective procedures		
Partitioning	3.24*	2.25
Memory-directed sampling	4.96	4.37
Evaluation	4.00	3.82
Imagery	5.05*	4.12
Pattern encoding	4.90**	3.68
Relation encoding	4.46**	3.04
Neutral Procedures		
Mnemonics	1.14	1.79
Spatial labeling	2.18	1.98
Rehearsal	4.52	4.70
Association 1	2.10	1.81
Association 2	0.35	0.75
Association 3	1.44	1.15

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

poor learners did not differ in their use of the Neutral Procedures. These results replicate the findings in Experiment 1 and further indicate the efficacy of the effective learning procedures.

Effects of Training

To determine the effects of instruction on the use of these procedures, we compared the pretraining and post-training scores for subjects in the three groups. Separate analyses of variance were performed for recall of complete map elements, recall of spatial attributes, and recall of verbal attributes. Figure 4 shows the data for recall of complete map elements. Overall, the mean recall score for the second map was greater than that for the first map, $F(1,40) = 71.31, p < .001$. The main effect for training group was not significant ($F < 1$). More importantly, however, the predicted map by treatment interaction was reliable, $F(2,40 = 3.32, p < .05$. A planned comparison confirmed that the Effective Procedures group recalled more on the post-training map than the Neutral Procedures and No Procedures groups, $t(80) = 4.49, p < .001$.

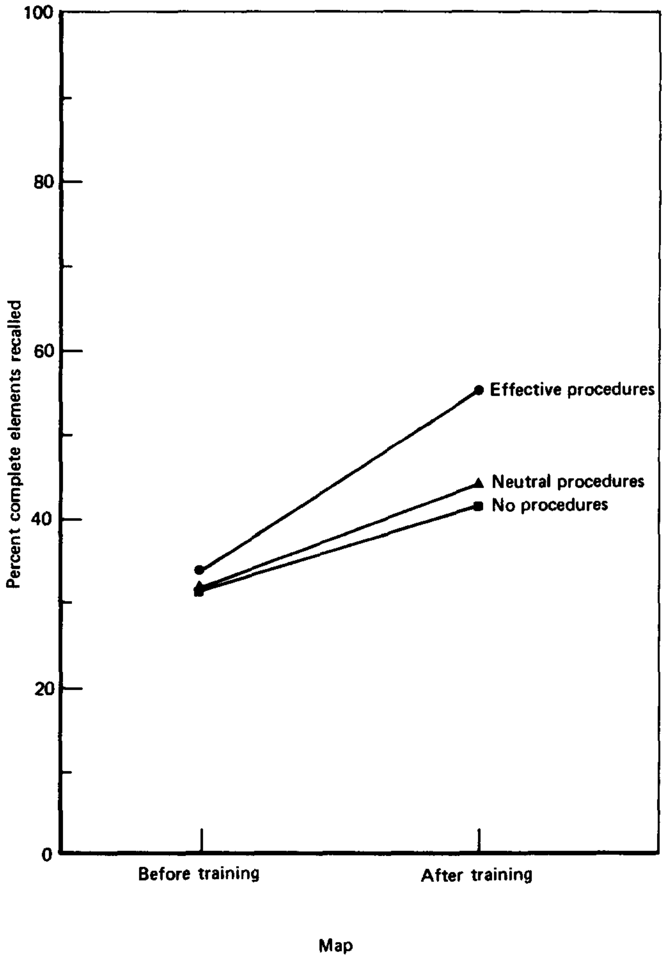

FIG. 4. Mean recall across trials of complete elements in Experiment 2.

Figure 5 displays the results for recall of spatial and verbal attributes. Recall of spatial attributes (Fig. 5A) improved from the first to the second map, $F(1,40) = 70.27$, $p < .001$. While group differences were in the expected direction, the interaction fell short of significance, $F(2,40) = 1.81$. However, a planned comparison indicated that the Effective Procedure group recalled more on the post-training map than the other two groups ($t(80) = 3.48, p < .001$). In contrast, recall of verbal attributes was nearly identical across maps and groups (see Fig. 5B).

To further explore the group differences on the post-training task, performance on the second map was analyzed by trial. Figure 6 presents the

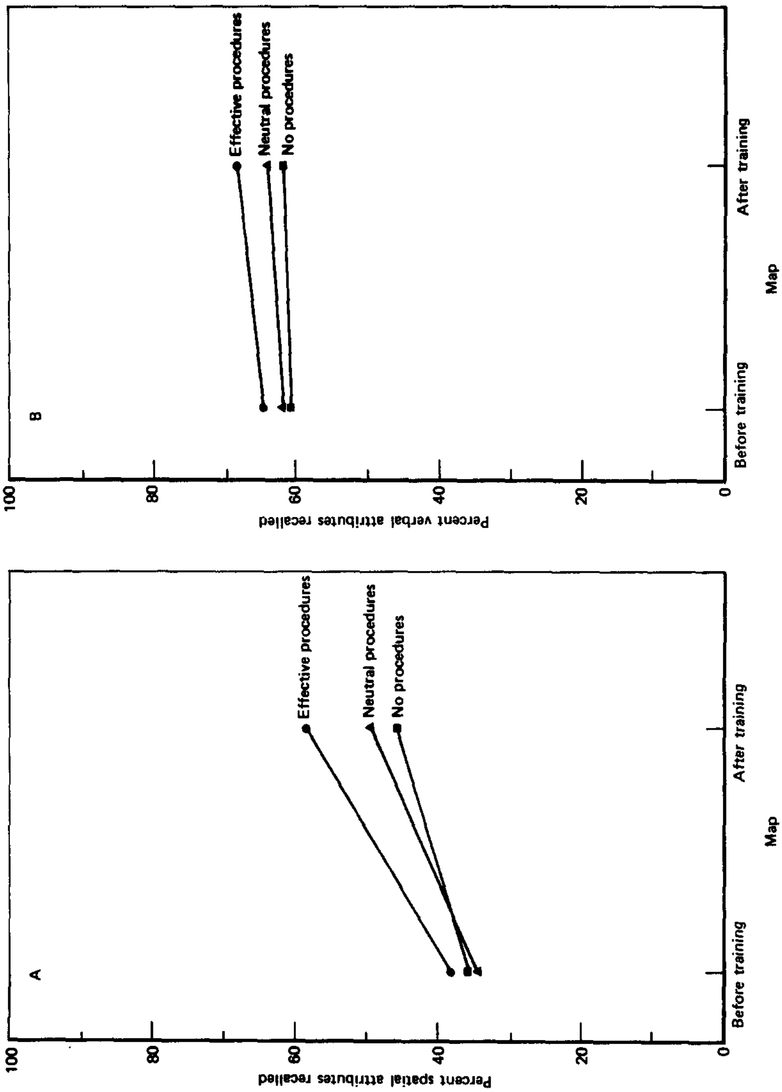

FIG. 5. Mean recall across trials of spatial attributes (A) and verbal attributes (B) in Experiment 2.

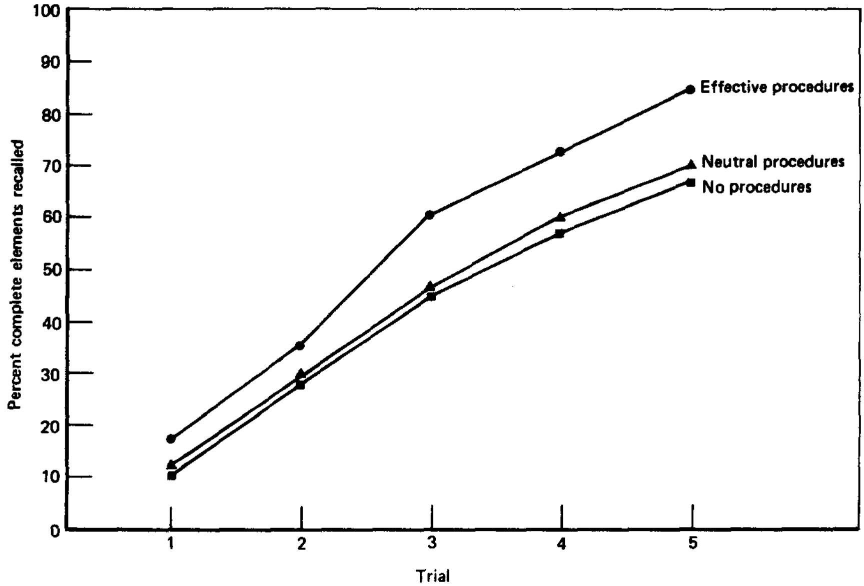

FIG. 6. Recall of complete element by trial in Experiment 2.

data for complete element recall. While the Effective Procedures group was superior on all trials, the main effect for treatment was only marginally reliable ($F(2,160) = 2.38, p < .10$), and the interaction was not significant ($F(8,160) = 1.04$). However, as Fig. 6 shows, the Effective Procedures group showed a marked improvement in recall after Trial 2 relative to the other groups. Post-hoc comparisons declared the means for the Effective Procedures group to be larger than those for the Neutral Procedures group at trials 3, 4, and 5 ($p < .01$ for all comparisons).

Figure 7 represents the data for recall of spatial and verbal attributes by trial. For spatial recall (Fig. 7A), comparisons of individual group means replicated the pattern of results in recall of complete elements. The Effective Procedures group had significantly higher recall than the Neutral Procedures group on the last three trials ($p < .05$ for all comparisons). For verbal attributes, the interaction between group and trial was reliable ($F(8,160) = 2.12, p < .05$).

As these analyses indicate, the advantage of the Effective Procedures training was not apparent until the third trial on the post-training map. This delayed effect may have been due to the fact that two of the effective procedures (memory-directed sampling and evaluation) could not be used until at least trial 2. Memory-directed sampling required the study of particular map information on trial n that had not been recalled on trial $n - 1$. Evaluation required subjects to compare perceived map information

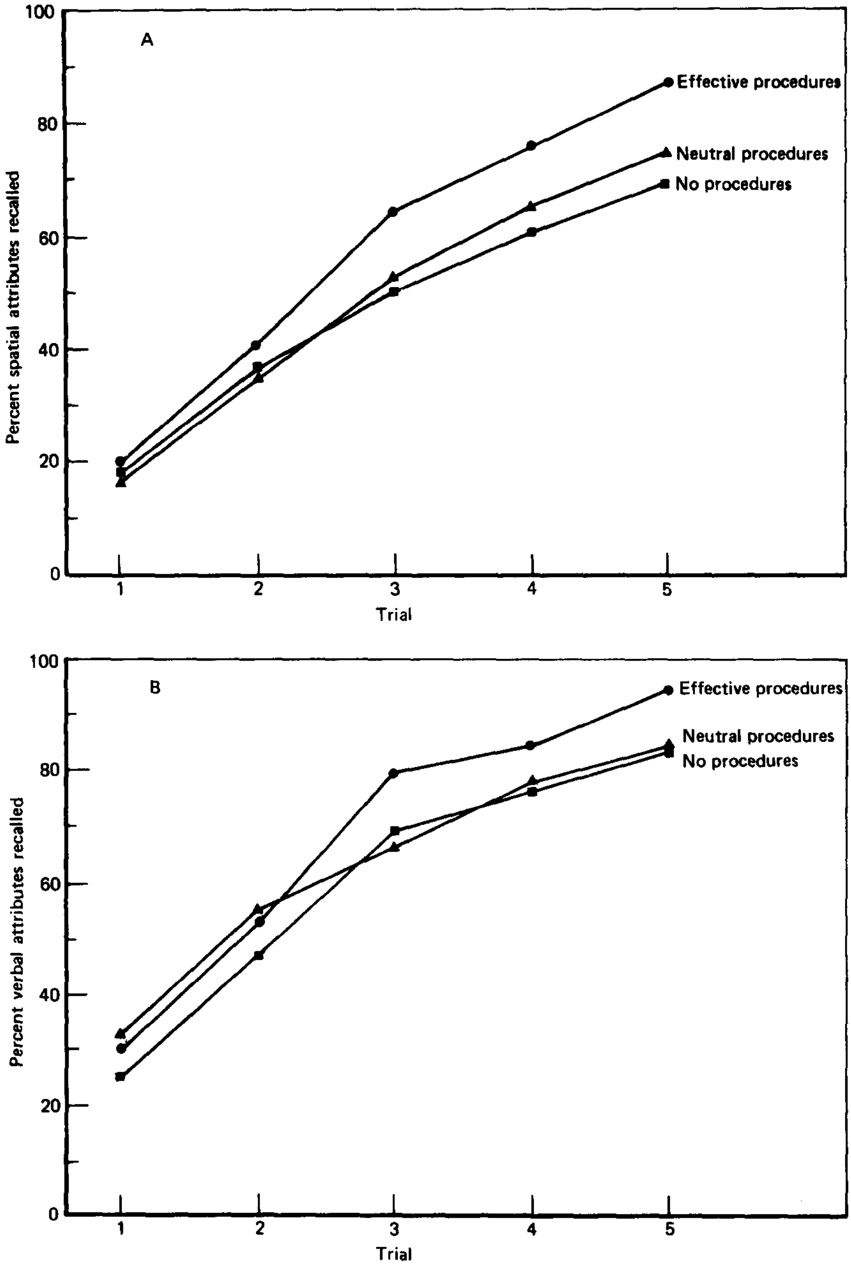

FIG. 7. Recall of spatial attributes (A) and verbal attributes (B) by trial in Experiment 2.

on trial n to their recall of that information on trial $n - 1$. In addition, these techniques are most effectively employed when much of the map has already been learned. Therefore, these procedures may not have been used extensively until later trials.

Assessment of Post-Training Procedure Use

Presumably, the superior improvement of the Effective Procedures group over the other groups occurred because these subjects used the trained procedures (hereafter referred to as target procedures). To test this assumption, we scored the questionnaires to determine the frequency of use of procedures before and after training.

Table 6 shows the mean ratings for the use of Effective and Neutral procedures by the three groups. The results confirm that subjects did in fact increase their use of target procedures after training. The first three rows indicate that effective procedure usage increased significantly after training for subjects instructed to use those procedures, $t(13) = 2.42, p < .05$, but did not increase for the Neutral Procedures or No Procedures groups. Similarly, the Neutral Procedures group reported more frequent use of target procedures on the second map than on the first, $t(15) = 2.31, p < .05$. However, usage of these procedures did not increase for the other two groups.

To further support the conclusion that the use of the effective procedures improved performance, we computed within-group correlations between the reported use of effective and neutral procedures on the second map and the increment in recall across maps. This increment was measured as the difference in percentage recall on the last trial of the two maps. Table 7 shows the correlations for recall of complete elements, spatial attributes, and verbal attributes. As expected, the use of effective procedures correlated reliably with improvement in complete element and

TABLE 6

Mean Reported Frequency of Use of Effective and Neutral Procedures

	Before training	After training
Effective Procedures		
Effective Procedures Group	3.74*	4.44*
Neutral Procedures Group	3.45	3.72
No Procedures Group	4.38	4.23
Neutral Procedures		
Effective Procedures Group	2.18	2.14
Neutral Procedures Group	1.96*	2.53*
No Procedures Group	1.75	1.91

* $p < .05$.

TABLE 7

Correlations between Mean Use of Procedures after Training and Recall Increment

	Effective Procedures			Neutral Procedures		
Treatment	Complete elements	Spatial attributes	Verbal attributes	Complete elements	Spatial attributes	Verbal attributes
Effective Procedures Group	.59*	.55*	.42	.16	−.23	−.12
Neutral Procedures group	.31	.32	.08	.17	.06	−.15
No Procedures Group	.02	−.05	−.43	.03	−.41	−.54*

* $p < .025$.

spatial recall for subjects trained to use these techniques. That is, the more frequently subjects used the effective procedures, the greater their improvement in performance. Three of these procedures (imagery, pattern encoding, and relation encoding) operated on spatial information, while the other three (partitioning, memory-directed sampling, and evaluation) were equally applicable to spatial and verbal information. Therefore, we expected that the correlation between procedure use and performance increment would be higher for spatial attributes than for verbal attributes. As the first row of Table 7 shows, this expectation was confirmed. In contrast, we found no evidence that the use of Neutral Procedures facilitated learning.

Visual Memory Ability

In light of the important role of spatial learning procedures in determining overall learning success, we expected that subjects' visual memory ability would affect success on the learning task. In particular, since imagery and perhaps pattern and relation encoding depend on the use of a visualization process, the effectiveness of training these procedures might depend on the ability to visualize spatial configurations in memory.

The analysis of the *Building Memory Test* scores provided data on subjects' visualization ability. The reliability of this test, estimated by the Spearman–Brown formula, was .76. The mean scores on the 24-item test were 17.61 for the Effective Procedures group, 18.48 for the Neutral Procedures group, and 15.48 for the No Procedures group. An analysis of variance indicated that the groups were indistinguishable in visual memory ability. Across all subjects, the correlations between visual memory and complete element recall ($r = .54$), spatial attribute recall ($r = .55$), and verbal attribute recall ($r = .44$) on the pretraining map were all significant

($p < .01$). The same correlations between ability and post-training performance were also reliable ($r = .63$, .66, and .34, respectively, $p < .01$).

To determine if training differentially influenced post-training performance for subjects with different visual memory ability, we performed a linear regression of performance increment on training group and ability. Figure 8 displays the increment in recall of complete map elements as a function of ability for each of the training groups. The solid lines represent the best-fitting function for each group, and the dashed lines display the 95% confidence interval for the predicted recall scores. As Fig. 8 shows, recall increment increased with ability only for subjects in the Effective

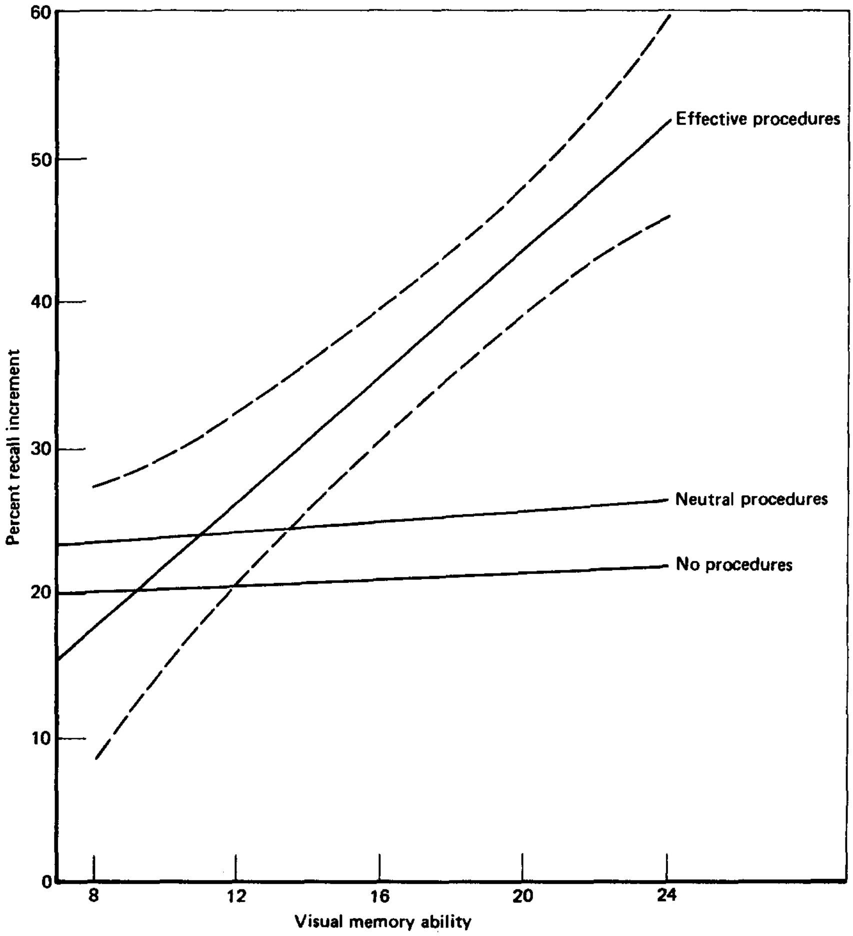

FIG. 8. Best-fitting regression line of recall increment (complete elements) on visual memory ability in Experiment 2.

Procedures group. We wished to determine for what levels of ability the Effective Procedures training produced significant improvements relative to the other groups. We therefore used the prediction equations to contrast performance increment for hypothetical high ability (ability score = 24), medium ability (= 17.41, the mean score across subjects), and low ability (= 10) subjects. For high and medium ability, the increment for the Effective Procedures group was reliably larger than the mean increment of the other two groups ($t(37) = 3.23, p < .01$ for high ability, $t(37) = 2.32$, $p < .01$ for medium ability).

Figure 9 shows the increments in recall of spatial (top) and verbal (bottom) attributes as a function of Visual Memory ability. For recall of spatial attributes, the increment for Effective Procedures training was reliably greater than for Neutral and No Procedures training for high and medium ability subjects ($p < .01$ for each). For recall of verbal attributes, the group differences were smaller and were reliable only for high ability subjects ($p < .05$).

The finding that high visual memory subjects benefitted most from training suggests that these subjects might have had an advantage over relatively low ability subjects in successfully using the trained procedures. This advantage could arise from three sources. First, subjects with high visual ability might be more inclined to choose the spatial learning procedures on their own, and thus they presumably would be more practiced at using the procedures. The first two columns of Table 8, however, suggest that this was not the case. The first column gives the correlations across all subjects between visual memory ability and the use of the six effective procedures on the first map, prior to training. The second column gives the same correlations for the subjects in the Effective Procedures group. None of these correlations is statistically significant. Thus, there does not appear to be a strong relationship between the choice of any effective learning techniques on the pretest and visual memory ability.

The second possible explanation for the superior improvement of high ability subjects is that they used the effective procedures more frequently after training than the low ability subjects. Subjects with low ability may have been less inclined to follow instructions to use techniques requiring visual memory than subjects with good visual memory. Across all effective procedures, the increment in frequency of use from the first to the second map was uncorrelated with ability ($r = .04$). However, as the last column of Table 8 shows, this correlation varied for individual procedures. For two of the three nonspatial procedures, low ability subjects increased their frequency of use relatively more than high ability subjects. In contrast, we found positive correlations between increased use of the spatial procedures and ability. Thus, as the third column of Table 8

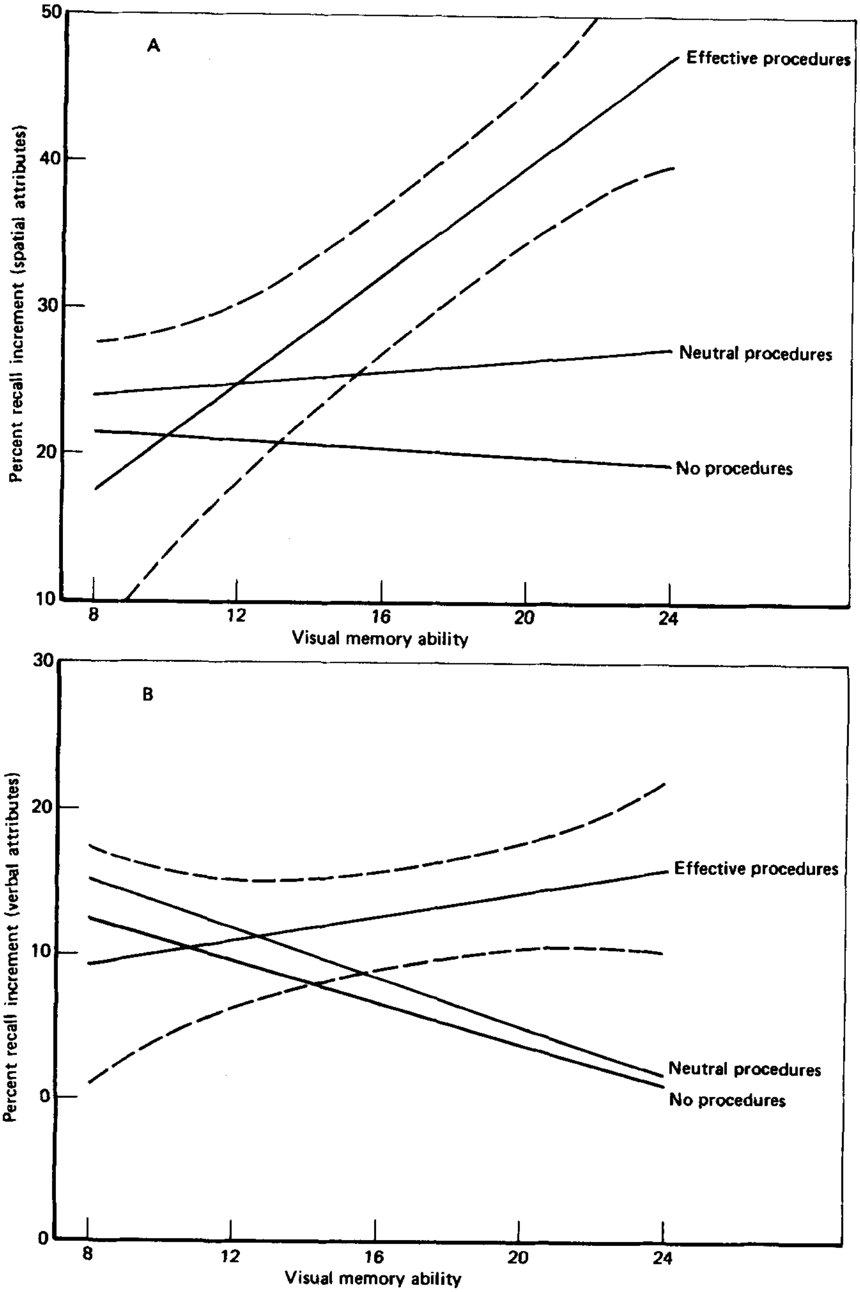

FIG. 9. Best-fitting regression line of recall increment for spatial attributes (A) and verbal attributes (B) on visual memory ability in Experiment 2.

TABLE 8

Correlations between Visual Memory Ability and Effective Procedure Usage

	All subjects	Effective Procedures Group		
Procedure	Before training	Before training	After training	Increment
Partitioning	−.01	.36	−.23	−.44
Memory-directed sampling	.08	.37	.22	−.30
Evaluation	.07	.27	.35	.15
Imagery	.11	.27	.50*	.24
Pattern encoding	.15	.02	.24	.20
Relation encoding	.27	.22	.43	.29

* $p < .05$.

shows, high ability subjects used two of the spatial learning techniques considerably more frequently on the second map than their low ability counterparts.

Finally, the effectiveness of the spatial learning procedures probably depends on visual memory ability. Subjects with poor visual memory may find these techniques difficult to use successfully. Thus, each use of an effective procedure might be more beneficial for high ability than for low ability subjects. To test this hypothesis, we regressed performance increment on visual memory ability and increment in procedure usage across subjects in the Effective Procedures group. When the variance due to the differences in procedure usage was removed from the prediction equation, ability accounted for a significant 27.6% of the remaining variance in performance increment, $F(1,11) = 6.80$, $p < .025$.

GENERAL DISCUSSION

It is evident from these analyses that successful map learning depends on particular study procedures for selecting, encoding, and evaluating information. Our analysis of learning protocols in Experiment 1 revealed several detailed differences in procedure usage between good and poor learners. Good learners coped with the task's lack of structure by formulating a learning strategy. They first segmented and focused systematically on subsets of information from the map. They demonstrated a variety of successful techniques for encoding both spatial relationships and verbal labels. Finally, they evaluated their learning progress consistently and accurately, using knowledge of their own uncertainties to determine their subsequent fixations and study behaviors. In contrast, poor learners' behavior deviated in a number of ways from that of more successful learners. These deviations might be regarded as "bugs" in their learning procedures that retarded rapid learning. From our analysis of the performance of poor learners, we have catalogued 10 learning bugs. Each poor learner exhibited some of these bugs, but no learner exhibited all of them. The bugs are summarized briefly below. They are grouped according to type of process: 1 is a bug in attentional processes, 2–5 are bugs in encoding processes, 6–8 are bugs in evaluation processes, and 9–10 are bugs in control processes.

(1) *No Attention-Focusing Strategy.* Some subjects made no decision about how to partition and sample information from the map, so they were either overwhelmed by the amount of map information or studied the information haphazardly.

(2) *Ineffective Procedures.* Procedures employed to acquire information did not succeed in producing learning.

(3) *Inappropriate Procedures.* Procedures such as schema application were used to learn information but were inappropriate for the given materials.

(4) *Unavailable Procedures.* Some subjects could think of no procedures for learning certain information on the map. Typically, this meant a subject was unable to use imaginal procedures on complex spatial information. For example, a subject would decide to learn all the street locations but could think of no procedure for doing so.

(5) *Knowledge Integration Failure.* Some subjects could not integrate spatially two types of knowledge acquired during study of different subsets of the map. For example, a subject may have learned road shapes separately from city locations. An integration failure would result in errors in placement of roads with respect to cities.

(6) *Infrequent Evaluations.* Some subjects did not monitor their learning progress to determine future study behaviors.

(7) *Learned Information Reevaluated.* Some subjects frequently evaluated information they had already learned.

(8) *Inaccurate Evaluations.* Subjects inaccurately decided whether or not they had already learned an element.

(9) *Attentional Strategy Abandoned Prematurely.* Subjects might abandon a strategy for structuring and sampling the map information prior to its completion and then begin sampling elements randomly.

(10) *Evaluation Feedback Not Used.* After deciding that an element had not been learned, subjects would shift the focus of attention to a new element without studying the unlearned information.

In Experiment 2 we attempted to reduce or eliminate bugs 1, 2, 4, and 6–10 by teaching subjects how to use six procedures we had observed good learners employ frequently. This training did in fact improve subjects' performance relative to subjects who received no or irrelevant training.

While we obtained training group differences for recall of spatial attributes, the groups did not differ in recall of verbal attributes. In both experiments individual differences in recall of verbal information and in the use of verbal learning procedures were much smaller than for the spatial information. Further, virtually every subject learned more verbal than spatial information on the maps. Because college students typically learn primarily verbal information (e.g., textbooks, class lectures) they probably develop verbal learning skills and techniques. In contrast, students' relative lack of practice at learning spatial information may restrict their repertoire of learning techniques and highlight ability differences.

Accordingly, the success of the effective procedures instruction depended on subjects' visual memory ability. This ability was related both to how frequently subjects used the trained spatial learning procedures and to how successfully they executed them. Low ability subjects, who presumably have difficulty creating and holding visual images in memory, would have difficulty effectively using these spatial learning procedures. On the other hand, high ability subjects could readily use procedures requiring attention to spatial information and the use of imagery. Thus, while high ability subjects improved tremendously after training, low ability subjects improved no more than subjects in the other training groups.

While both learning procedures and abilities appear to be important contributors to performance, we cannot yet assess their relative importance. Additional research is required to investigate whether subjects with relatively low visual memory ability may be taught to effectively employ spatial learning procedures. This question hinges on the precise relationship between the low-level processes required to perform psychometric tests of visual ability and those required for the use of high-level procedures. Some very basic spatial abilities, such as visualization, may consist of one or a few elementary processes. We view learning procedures as program-like combinations of these low-level processes. Visualization, for example, may be a single component of a more complex procedure, such as evaluation. This procedure may require the visualization of information in the current focus of attention.

Traditionally, psychologists have viewed abilities as general traits relatively resistant to change. Many learning procedures, however, are presumably flexible skills that are trainable and may improve with practice (cf. Hasher & Zacks, 1979). Therefore, if low visual memory individuals cannot readily be taught to use spatial learning procedures effectively, then it would appear that their use is highly ability dependent. For these individuals, optimal instructional design might capitalize on other learner aptitudes. For example, learners might be taught to use procedures that depended on processes they were skilled at using. Subjects themselves appear to be particularly adept at selecting strategies that are well suited to their abilities (e.g., MacLeod et al., 1978). On the other hand, if subjects of all abilities given sufficient training can learn spatial processing techniques, current assumptions about the nature of abilities and their explanatory power as a stable source of individual differences would be seriously challenged.

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