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Learning from Maps and Diagrams

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This review of learning from maps and diagrams consists of two sections. The first section presents a theoretical framework for learning from maps and diagrams. The case is made that the symbol systems of maps and diagrams are sufficiently similar for them to be considered together. The theoretical framework is built around what is known of pre-attentive and top-down psychological processes. It accounts for the way people discriminate between symbols used in maps and diagrams and how they group them into clusters. The second section comprises a review of psychological and instructional research. This research provides support for a number of hypotheses arising from the theoretical framework. Many of these are based on the notion that maps and diagrams communicate a considerable amount of information by the way in which components are placed relative to each other and to the frame surrounding them. Evidence that configuration and discrimination are fundamental to learning from maps and diagrams is summarized in 10 concluding points.

KEY WORDS: maps; diagrams; configuration; discrimination.

INTRODUCTION

The purpose of this review is twofold. First, I present a theoretical framework that explains how people learn from maps and diagrams. An analysis of the symbol systems of maps and diagrams shows they operate in sufficiently similar ways to justify their being considered together. This means that many psychological processes function in the same way whether operating on maps or diagrams. Second, I present research related to various facets of the theoretical framework. I do not present an exhaustive review of the research. Rather, I discuss research that supports predictions

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arising from the theory about how information in maps and diagrams is processed and learned.

THEORETICAL FRAMEWORK

The theoretical framework I propose follows the direction taken by Salomon (1979). Salomon proposed that learning from any medium depends on how the medium's symbol system interacts with cognitive processes. Manipulation of the symbol system to change how objects and concepts are shown, or how they are placed relative to each other, causes psychological processes to act differently. For example, showing map features as small drawings rather than as labels enables their encoding in images as well as in words (Amlund *et al.*, 1985), making them easier to learn. Learning from maps and diagrams can only be understood once relationships between symbol systems and psychological processes have been determined.

I will make the case that it is especially important to determine how the symbol systems of maps and diagrams interact with pre-attentive psychological processes. These processes act early in perception, are independent of top-down cognitive control, operate in parallel, and draw little on cognitive resources. A person cannot therefore willfully influence them. (Pylyshyn [1984] calls them "impenetrable" for this reason.) I will argue that the spatial relationships among objects and concepts shown in maps and diagrams and the way they are shown are crucial to determining how information is organized pre-attentively.

Spatial relationships among objects and concepts affect processes I refer to collectively as *configuration*. These processes determine which objects or concepts appear to form clusters, the sequence in which objects are processed, and which objects later receive the most attention. How objects and concepts are shown affects their *discrimination*, or the ease with which one can be distinguished from another. Pre-attentive organization of information by means of configuration and discrimination predisposes a person to interpret maps and diagrams in particular ways once cognitive processes are brought to bear under the control of attention.

This review is concerned with any format that communicates through the display of objects and concepts and the relationships among them. The terms "map" and "diagram" are therefore used very broadly. Maps include all possible ways of representing a territory, for example: topographical maps, street plans, floor plans, and schematic maps (e.g., of bus and rail systems). Diagrams include illustrations that express conceptual relationships spatially, for example: flow diagrams, schematic drawings, organizational charts, diagrams showing text structure, time lines, and family trees. Largely excluded from discussion are graphs and charts which employ a somewhat different symbol system. Graphs show relationships between at least one continuous and one categorical variable as when temperature (a continuous variable) is plotted against months of the year (a categorical variable.) Charts show relationships between categorical variables — for example, to show the predominant ethnic group in different areas in a city.

The theoretical framework permits a number of predictions about learning from maps and diagrams. The ease with which configuration can be manipulated by varying spatial relationships among objects and concepts leads to the predictions that maps and diagrams: (a) are particularly effective for showing physical layout, how things are put together, and how they work; (b) can serve as schemata that help to organize information; (c) can make abstract ideas more concrete; and (d) allow people to use their spatial skills. The ability to manipulate the discriminability of objects and concepts by varying the way in which they are shown leads to the predictions that: (e) showing objects and concepts as drawings makes them more memorable; (f) increasing their discriminability draws attention to them and away from the "big picture"; and (g) varying their familiarity, ambiguity, color, and pleasantness affects where attention is focused and what is learned. Research on these predictions is presented in a later section.

A Common Symbol System

Maps and diagrams convey information in fundamentally the same way. Each is made up of components that are placed in specific relationships with one another on the page or screen. In this review, "component" refers to symbols, labels, shapes, or pictures that the map or diagram contains. Examples include conventional signs in maps, or drawings and written words in diagrams. Components are contained within a frame. The frame may be a rectangle drawn around the map or diagram, or it may be defined simply by the edge of the page or screen. Figure 1 illustrates these ideas as well as concepts presented in the following paragraphs. The circled numbers, lakes, and labels comprise the components in Fig. 1; the numbers, letters, and electronic symbols are the components in Fig. 2.

Figure 1 shows that each component in a map or diagram conveys information about its location and about itself (see Schlichtmann, 1985). The circled numbers in Fig. 1 indicate the destinations of hiking trails, described in an accompanying text. The stippling around Wenatchee indicates

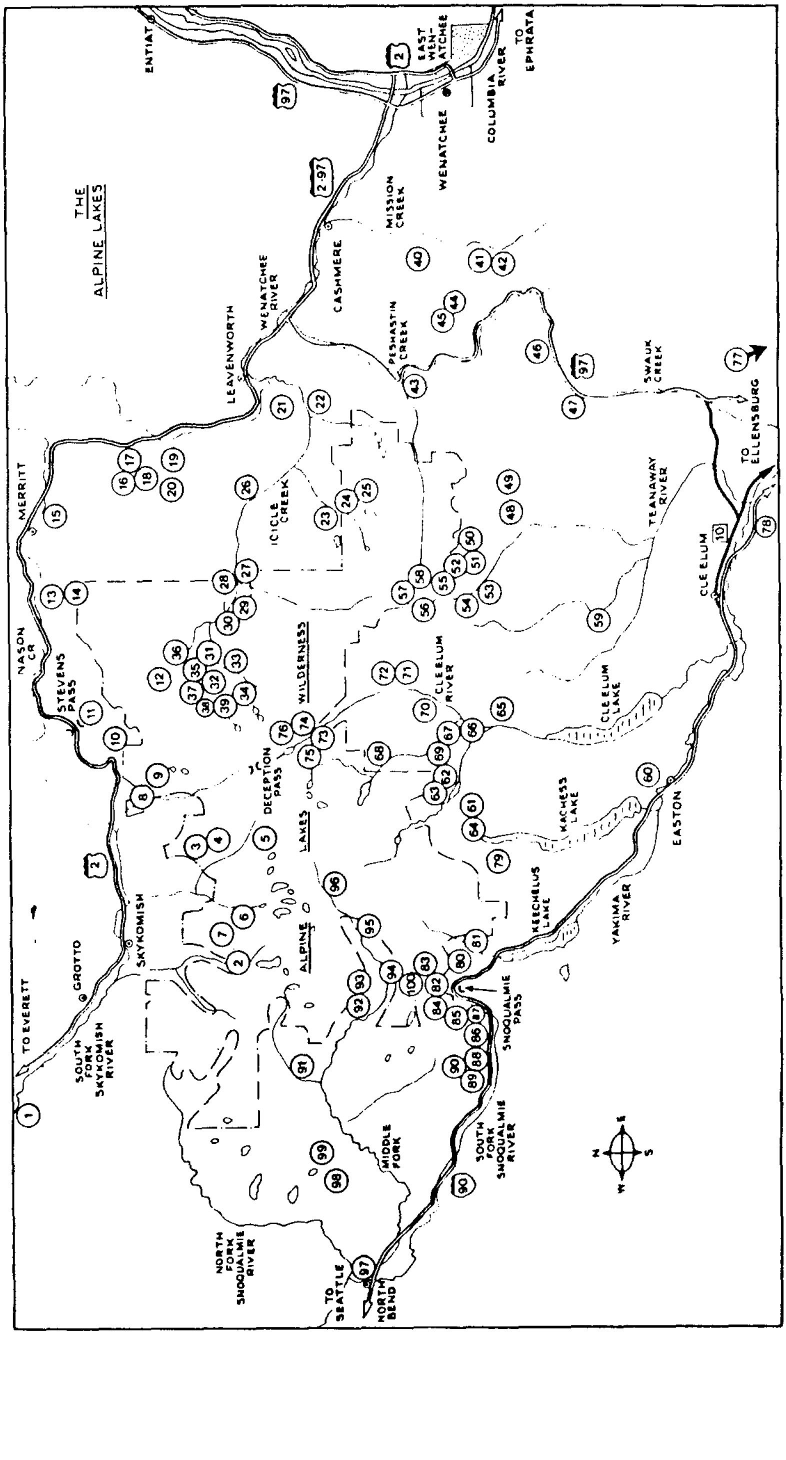

Fig. 1. Basic features of the symbol system of maps. From V. Spring, I. Spring, and H. Manning (1985), *100 Hikes in the Alpine Lakes* (Seattle, The Mountaineers), p. 6. Reprinted with permission.

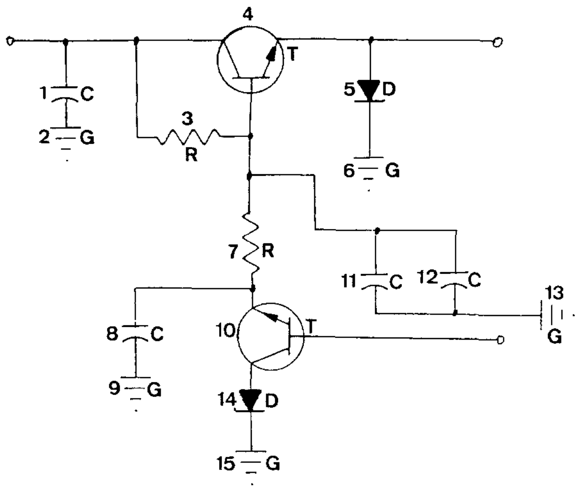

Fig. 2. Basic features of the symbol system of a diagram.

a built-up area. Each circle also indicates its direction and distance from other circles, because the map is to scale. Likewise, in the circuit diagram in Fig. 2, the symbols indicate whether the components are diodes, resistors, capacitors, or transistors. The relative location of the components and the lines that join them indicate how they are connected and the direction of the current.

Even such a simple symbol system, with just two ways in which to convey information, allows for a good measure of complexity and subtlety of expression. This results from the variability in how components and their relationships are displayed (Winn, 1989a,b, 1990). For example, the location of a component establishes *de facto* two types of relationships: (a) with the frame of the page or screen, and (b) with the other components. In the first case, the component might be at the top or bottom, or to the left or right of the frame. In the second case, it might be above or below, or to the left or right of another component, regardless of where it was situated relative to the frame. As we shall see, variations in placement of components in the frame and relative to other components have implications for cognition and learning.

Another important location variable is the distance a component lies from the frame and from other components. A component might be placed in the corner of the frame, or it might be placed more centrally. Components might be placed close to each other to form an obvious cluster, or distributed more evenly throughout the frame. These factors, too, have important psychological implications.

The components themselves can vary in a number of ways. The first concerns their *notationality*. The notationality of a symbol system (Goodman, 1968; Salomon, 1979) represents the uniqueness of the relationship between a component and some object in the domain of reference. In notational systems, such as most maps and diagrams, there is a clear one-to-one correspondence between a component and what it represents. The symbols for a church or for a transistor are unambiguous, and each time they are used they correspond to one particular object in the landscape or electronic circuit. By contrast, in nonnotational symbol systems, such as photographs, there is a less clear-cut relationship between components and their referents. The shadows or natural color in an aerial photograph make it difficult to distinguish one object from another or to tell where one feature ends and the next begins. By the same token, a photograph of the inside of a computer is far more difficult to interpret, insofar as the computer's structure and function are concerned, than a circuit diagram. Clearly, a component's notationality has a significant impact on how it is perceived, processed, and learned.

Components of maps and diagrams also vary in their *relative dominance.* Some components dominate others by virtue of their size, isolation, or color. They are therefore accorded more importance.

A component's *perceptual precedence* determines whether it is attended to early or late when the map or diagram is perused. Precedence concerns the "level" at which we "enter" the image. Do we notice the general configuration of the map or diagram first, or do we start with the details? Opinion on this matter has varied considerably over the years. Evidence for the precedence of global features suggests that we start with the whole and then work toward the details. Navon (1977) had undergraduates view tachistoscopically presented small letters arranged so that they formed a single large letter. The small letters were not necessarily the same as the large letter. Subjects responded yes or no to whether a large or small letter was present. Response latencies were quicker when the target letter was a large letter, a finding that suggested global precedence.

More recent evidence suggests that precedence is not absolute but determined by the size of the display. Using undergraduates, Kinchla and Wolfe (1979) replicated Navon's (1977) study with displays of different sizes. Response latencies were quickest for large letters only when the visual angle was six degrees or less. At angles larger than nine degrees, responses were quickest for small letters. Antes and Mann (1984) replicated aspects of Kinchla and Wolfe's study using pictures rather than letters. Undergraduates looked at a picture of a beach or a farm. In some pictures, one object was out of context. A tractor appeared on the beach, or a boat on the farm. Subjects were asked whether a beach or farm, boat or tractor, was present. Reaction times showed global precedence for small scenes subtending four degrees of visual angle, and local precedence for large scenes subtending 16 degrees of visual angle.

These findings support what Kinchla and Wolfe (1979) called a "middle out" account of precedence. Figures that have an optimal size are processed first. Details and more global configurations are processed later. Moreover, size is not the only factor that may influence precedence. How long the image is presented (Paquet and Merikle, 1984), whether or not components share a property with the complete figure (Lesaga, 1989), and the size of components within clusters (Kimchi, 1988) have been shown to have an influence. Research that has examined precedence in maps and diagrams is discussed in a later section.

A final example of common ground in the symbol systems of maps and diagrams is that the relationships among components can convey information about both patterns and sequences. More than 20 years ago, Knowlton (1966) pointed out that pictures can use either one or two dimensions to give information (see also Moxley, 1983). For example, a yachtsman at sea uses the two-dimensional patterns formed by visible features (such as coastlines, rocks, and aids to navigation) and their relative positions on a chart made meticulously to scale. It is only from these patterns that the yachtsman can take bearings and plot an accurate position. On the other hand, a bus passenger is only concerned about the order of bus stops and not whether the route map is made to scale (usually, it is not), provided that it shows the sequence of stops and major intersections in the correct order. Similarly, an electrical engineer who designs circuit boards perceives a circuit diagram one-dimensionally when determining which component is connected to which, and two-dimensionally when optimizing the distances among components and thus increasing the speed at which the circuit operates.

There are nonetheless some differences between the symbol systems of maps and diagrams. Such differences mostly concern domains of reference rather than intrinsic structures. For example, maps always refer to concrete objects in a real territory. Diagrams may refer to concrete objects, as when they represent the stages in the oil-refining process. However, diagrams may also represent intangible concepts, such as corporate structure. In such cases, the way components are shown and the spatial patterns they form are frequently analogical. For example, the "higher" a person is on a company's organizational chart, the more influence the person has in the company. The "height" of the person on the chart does not indicate the floor on which their office is located as it might in a building plan.

This distinction between what maps and diagrams may refer to helps explain why scale is important in maps but less so in diagrams. It also explains why maps and diagrams may be interpreted differently even though they are perceived and organized by the same psychological processes. In the discussion that follows, I will therefore separate factors that influence the structure of information contained in maps and diagrams from those that affect their interpretation. This distinction is not unlike that made between the syntactic and semantic aspects of illustrations (Goldsmith, 1984, 1987; Kosslyn *et al.*, 1983; Winn, 1989b). The former have to do with the structure of images, the latter with what they mean.

Structure: The Configuration of Components

A great deal of perceptual organization takes place pre-attentively (Marr, 1982; Marr and Nishihara, 1978). As I mentioned earlier, the processes involved are not accessible to conscious cognitive control. Two such processes are particularly important in the perception of maps and diagrams: (a) the *configuration* of parts into potentially recognizable components and of components into clusters, and (b) the *discrimination* of individual components from each other. These processes are not always separate, although for convenience I will treat them as such. The processes act prior to such semantic tasks as recognition, identification, and interpretation. Indeed, meaning cannot be ascribed to a map or diagram until its components have been configured. Similarly, discrimination among components is a precursor to such higher-level cognitive tasks as categorizing information into concepts and applying rules to solve problems (Gagne, 1985).

The pre-attentive configuration of components has received considerable attention (Pomerantz, 1981, 1986; Pomerantz and Garner, 1973; Pomerantz *et al.*, 1989; Pomerantz and Schwaitzberg, 1975; Treisman, 1988; Treisman and Gelade, 1980; Uttal, 1988). First, this research provides a tentative answer to the question, "What exactly is a component?" Pomerantz (1981) has suggested that parts configure into components when selective attention fails to be paid to each separately. Thus, even pre-attentively, we see a triangle as a single component, not as three separate lines. A component is therefore an emergent property (Rock, 1986) of its parts that are attended to simultaneously. [In a similar vein, but on a larger scale, Szlichcinski (1980) has noted that the meaning of a whole diagram is greater than the meaning of the sum of its parts.] The distance between parts also affects how easily they configure to form components

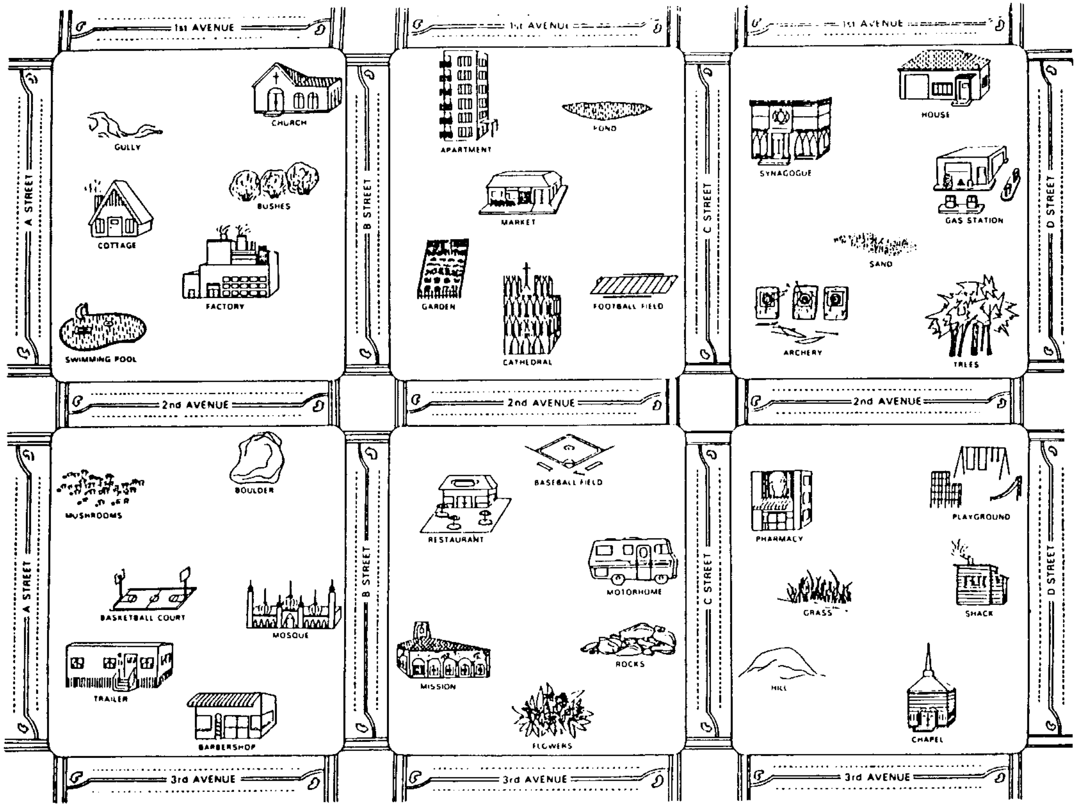

Fig. 3. Component hierarchies in a map. From R. W. Kulhavy, N. H. Schwartz, and S. H. Shaha (1982), Interpretative framework and memory for map features, *The American Cartographer*, Vol. 9, pp. 141–147. Reprinted with permission.

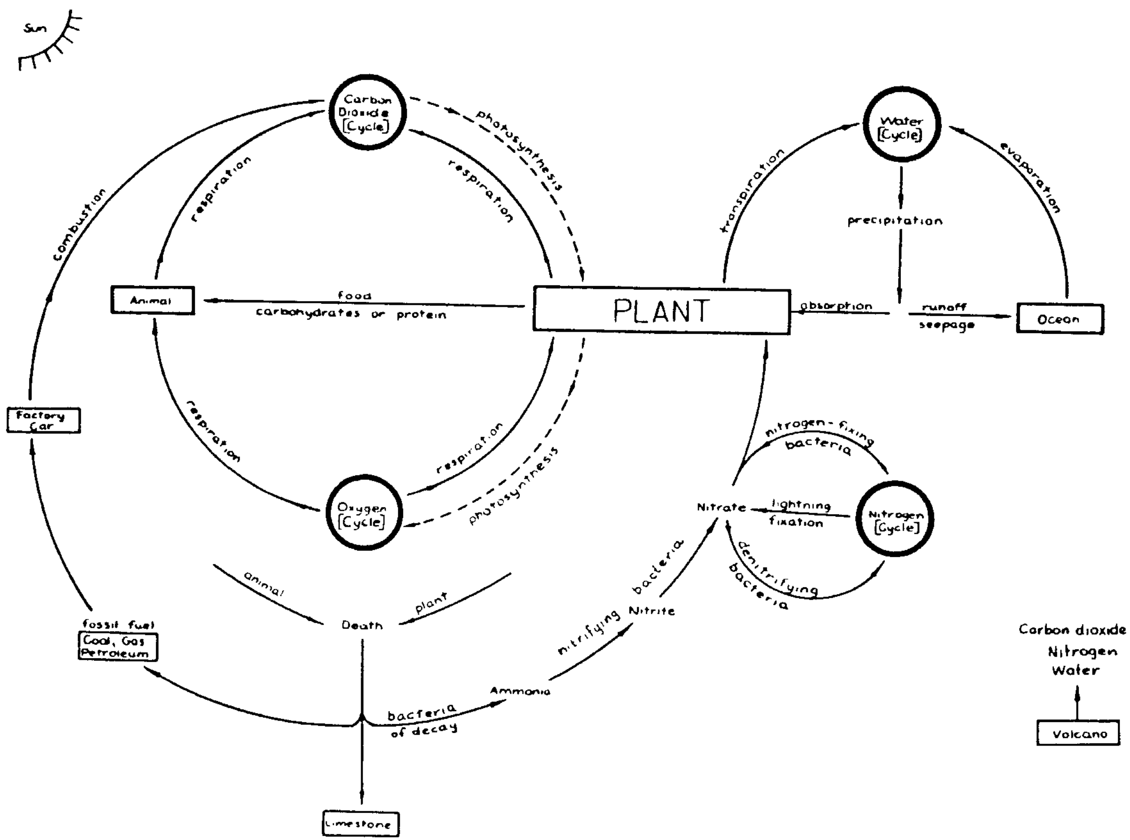

Fig. 4. Component hierarchies in a diagram. From W. G. Holliday (1976), Teaching verbal chains using flow diagrams and texts, *AV Communication Review*, Vol. 24, pp. 63–78. Reprinted with permission.

(Pomerantz and Schwaitzberg, 1975). The closer the parts, the more easily they configure to form components.

One property of the symbol system of maps and diagrams is that their components can form clusters, which in turn can form other clusters in a hierarchical fashion. Each cluster can then act as a discrete component. Figure 3 illustrates this. The map, used by Kulhavy *et al.*, (1983) in a study described later, can convey information at three levels of detail. At one level, each city block acts as a component and the map "tells" the viewer about how the blocks are arranged. At the next level, the components are the buildings and other features in each block. The map identifies them by name and shows their relative locations. At the last level, the parts of each feature, like the mission's bell and the factory's chimney, are the components. These help us discriminate and identify each feature in the city. The diagram shown in Fig. 4, from a study by Holliday *et al.* (1977), also described later, functions in a similar way. First, it shows how the water, oxygen, nitrogen, and carbon dioxide cycles interact. Next, it shows interactions among components within each cycle. Last, it shows the different attributes of each component in drawings, making them easier to discriminate and remember.

Early perceptual organization is influenced by the hierarchical structure of components in maps and diagrams. Thus, components in close proximity tend to be associated with each other and to form distinct groups that can act in turn as single components. When components are surrounded with a boundary, the likelihood increases that they will be seen as a single group. The presence of a boundary line between even two relatively close components is sufficient to have them assigned to different groups (McNamara, 1986).

There is a certain consensus among psychologists that *chunking* information in this way facilitates memory and retrieval. Chunking is a strategy used by people skilled in memorization (Chase and Ericsson, 1982; Ericsson and Staszewski, 1989; Frick, 1989). Rather than having to recall each individual item, one can recall the chunk and "unpack" it to see what is inside. Helping people chunk materials by arranging them in clusters on the page or screen has proven effective for a variety of memorization tasks. These include learning word lists (Bellezza, 1986; Decker and Wheatley, 1982), letter patterns (Winn, 1986), and map features (Sutherland and Winn, 1990). Visual chunking has also been observed in individuals working with computer spreadsheets (Saariluoma and Sajaniemi, 1989), and in the recall, by expert technicians, of components in circuit diagrams (Egan and Schwartz, 1979). Finally, learning strategies involving chunking is useful to subjects learning maps (Thorndyke and Stasz, 1980) and diagrams (Winn and Sutherland, 1989).

Structure: The Discrimination of Components

The second major characteristic of maps and diagrams that has significant psychological implications is the discriminability of individual components. Even before meaning is ascribed to them, components that look alike tend to be associated with one another.

The discrimination of components in maps and diagrams can be facilitated in a number of ways. Components can be discriminated on the basis of color, shape, size, and complexity, to name but four relevant dimensions. Research investigating the search for targets in visual displays (Treisman, 1986; Treisman and Gelade, 1980) has shown that components, such as letters, are discriminated on the basis of color and shape; and that when only one dimension distinguishes the target, search is parallel, drawing little on cognitive resources and making detection easy and automatic. If discrimination is based on more than one dimension, say on both shape and color, then search is serial, slow, and demanding of cognitive resources. For example, it is easy to find a red *X* in a field of blue *X*s, and much harder to find a red *X* in a field of red and blue *X*s and *Y*s.

It follows from this research that increasing the number of dimensions along which components vary makes them more difficult to discriminate. Although this conclusion is contrary to conventional wisdom, there is some evidence that it is the case. Samet *et al.* (1982) found, for example, it was more difficult to find military tactical units on battlefield maps when they were represented as icons (pictorial representations) than when they were shown as conventional symbols. The greater complexity of the icons required more effort before accurate discriminations could be made. Similar results have been reported from research on computer interfaces (e.g., Arend *et al.*, 1987) and on human factors (e.g., Remington and Williams, 1986).

Once the meaning of components on maps and diagrams has been learned, however, the detrimental effect of their complexity on discrimination is attenuated. It has been shown (Winn, 1988) that representing components of unfamiliar material (circuit diagrams) as icons rather than as labeled boxes reduces recall of component locations. The greater effort needed to discriminate the components draws attention and effort to the components themselves and away from the "big picture" in which locations are shown. In the case of maps, however, where the symbols for components are already known to the subjects, iconic representation for components enhances recall (Sutherland and Winn, 1987). It appears that complex symbols for components on maps and diagrams hinder discrimination when the material is unfamiliar.

Meaning: The Configuration of Components

I will now describe how meaning is ascribed to maps and diagrams under the top-down control of attentional processing. Again, I will examine both the configuration and the nature of components, beginning with configuration.

The question is, "How do changes in component configuration affect the meaning of the map or diagram?" The answer to this question has both psychological and cultural aspects. As to the former, we tend to "read" maps and diagrams as we read text: from left to right and from top to bottom (Brandt, 1945); and the order we encounter components profoundly influences the way we interpret them. As for the latter, our interpretation derives in large part from conventions of cartography and the graphic arts, which are frequently specific to a particular time or culture. Salomon (1979) pointed out that, in contrast to practice dictated by today's conventions, medieval cartographers used maps to show historical events as well as geographical locations. In medieval maps of the Holy Land, for example, Jerusalem may be shown more than once, and "Moses reappears all over the map" (p. 64).

Studies have also shown that people from different cultures respond in different ways to illustrations (Deregowski, 1989; Deregowski and Dziurawiec, 1986; Mangan, 1978). Deregowski's (1989) review of this research makes the case that different skills are involved in perceiving the real world and illustrations of the real world. In cultures where there is no tradition of pictorial representation, skills more appropriate to perceiving the real world are applied to illustrations, making them hard to understand. Mangan's (1978) review of pictorial representation in different cultures gives some good examples of this. An elephant has four legs. Therefore, the animal is represented by some African tribal artists as "spread-eagled" so that all of its legs are visible.

I have pointed out how the spatial dimension of symbol systems conveys information about both the absolute and relative locations of components and about their sequence. Variation of component location in maps and diagrams affects how sequences and relationships among components are interpreted. Reversing the "natural" sequence of steps in a diagram from left-to-right to right-to-left significantly reduces subjects' ability to recall sequences and to classify components into correct categories (Winn, 1982). In many diagrams [and certainly in the ones used in Winn's (1982) study] the symbols and labels for superordinate categories appear above and sometimes to the left of the components that represent subordinate concepts. Thus, the component "mammal" is likely to appear above or to the left of the component "cat" in a diagram illustrating families of animals. This means that it will be read first, and will provide a category into which subsequent components can be placed. If the flow of the diagram is reversed, then subordinate components will be encountered before superordinate categories, making the diagram harder to understand. Winn (1983) observed eye movements of graduate students as they studied conventionally arranged and reversed diagrams and found that subjects initially scanned from left to right and top to bottom even with reversed (right-to-left, bottom-to-top) diagrams. These subjects found it very difficult to find the information needed to answer questions and to identify the sequences in which events occurred.

Encountering superordinate categories before subordinate ones is one example of how graphical conventions influence interpretation of maps and diagrams. A more recent study (Winn, 1989c) has examined other conventions. Subjects in this study were forced to choose between pairs of sentences interpretating simple two-component diagrams in which each component was a nonsense word. The interpretations involved three types of relationships: class membership ("A yutcur is a zogwit"), attribution of properties ("A yutcur has a zogwit"), and causality ("A yutcur causes zogwit"). Some very clear biases in interpretations were found. For example, attributes were perceived as components on the right of, below, or inside the other component. Causes were almost always the component to the left of, above, or outside the other. In addition, diagrams with components side by side were usually interpreted as showing causality rather than attribution; those with components one above the other were more often interpreted as showing attribution and causality than class inclusion. Many other such relationships were found. It is clear that the way components are configured affects how diagrams are interpreted.

Meaning: The Nature of Components

In the discussion of discrimination, I have considered how meaning is ascribed to individual components in maps and diagrams. I now look further at how components themselves are comprehended by discussing component recognition.

Although opinions vary, there is consensus that individuals recognize objects and pictures of objects on the basis of their parts (Biederman, 1987; Hoffman and Richards, 1984; Marr and Nishihara, 1978). The identification of just a few parts is often all that is needed for an object to be recognized. In Marr and Nishihara's account, for example, the identification of cylindrical shapes varying in length, orientation, and thickness is all that is necessary for an individual to recognize a person, bird, or giraffe.

The "parts" approach to theories of recognition has the advantage of accounting for how objects and their representations can be recognized even when viewed from novel or unusual points of view. We recognize a symbol representing a factory on a map regardless of the angle from which the factory is depicted. This is because the association of the percept and a schema in memory need only be made on the basis of a few characteristics for the schema to become active and accessible to verification (Norman and Rumelhart, 1975). This account of recognition has superceded template-matching theories of recognition which have been largely discredited because they require vast memory storage and matching on many dimensions (Pinker, 1985).

The emphasis on parts means that research on recognition has much in common with research on concept learning. This is true whether concepts are learned by identifying critical attributes (Engelmann, 1969; Merrill and Tennyson, 1977) or by recognizing prototypes (Rosch and Mervis, 1975). The evaluation of critical attributes against existing schemata provides a reasonable account of how components of maps and diagrams might be recognized once they have been discriminated from each other pre-attentively.

Summary

The theoretical background relevant to learning from maps and diagrams rests on a large body of research. Of prime importance, however, is how components and their configuration affect cognition. As I have presented it, this theoretical framework comes from relatively basic research on human perception and cognition, and from research that used maps and diagrams to study cognition rather than to study the instructional effectiveness of maps and diagrams. Yet the theory should be able to predict learner performance in research where maps and diagrams have been studied for their own sake. It is to this body of research that I now turn.

RESEARCH ON LEARNING FROM MAPS AND DIAGRAMS

This section presents evidence for and against certain expectations for learning that arise from the theoretical framework. Although this framework assumes maps and diagrams have largely similar symbol systems that operate in similar ways on cognitive processes, in this section, which deals with attentive processing, I acknowledge the differences between the two representational forms. Maps represent territories in literal and realistic ways, whereas diagrams represent their domains of reference analogically. Thus, the literature on learning from maps stresses such skills as estimating distance, navigating, and understanding spatial relationships. The literature on diagrams, on the other hand, discusses the metaphorical use of space to improve memory and comprehension of more abstract content, such as processes and structures that cannot be directly observed.

Learning from Diagrams

Larkin and Simon (1987) offered a detailed account of how component configuration in a diagram might lead to improved comprehension. They proposed production system models that describe how subjects process information presented as sentences and diagrams in order to solve physics and geometry problems. A comparison of their sentence processing and diagram processing models shows how component clustering and placement in diagrams make it easier to find information and to use it effectively.

Larkin and Simon's account revolves around the idea that two-dimensional displays (diagrams) can convey more information about relationships than one-dimensional displays (text). If a subject is asked to solve a problem from information presented as text, the first relevant piece of information has to be found and stored in memory while the next relevant piece is sought. It too has to be remembered, while the text is searched for the next piece of information. The process continues until all the relevant information has been found. The learner must draw heavily on memory and search strategies, and is also prone to error. On the other hand, once the first piece of relevant information has been found in a diagram, it is very likely that the next piece will be found next to it. This reduces the need to search through a lot of information, and also makes it unnecessary to remember anything, as both pieces of information can be inspected at once. What is more, this inspection readily reveals the path to the next piece of information. Far fewer cognitive resources are necessary, with the result that comprehension and problem-solving are greatly facilitated.

What Larkin and Simon described is one example of *visual argument* (Waller, 1981). Visual argument is defined as the transmission of information primarily through the spatial arrangement of components. Some have even suggested that visual argument uses a completely different system of logic than text and that some forms of visual argument can only be expressed through diagrams (Doblin, 1980; McDonald-Ross, 1979).

Evidence exists for cognitive processes that are particularly effective in dealing with visual argument. Mental models have been proposed to represent how humans understand and interpret the world. Mental models use spatial relationships among concepts to describe how information is encoded (Anderson, 1983; DeKleer and Brown, 1981; Johnson-Laird, 1983; Mani and Johnson-Laird, 1982). The construction and use of accurate mental models should therefore also be facilitated through diagrams, and should in turn help in their interpretation.

The experimental evidence for the instructional effectiveness of visual argument in diagrams, and the identification of factors that attenuate its effectiveness, is plentiful. The following are selected studies that exemplify certain aspects of this work and thereby illustrate a number of facets of the theoretical framework.

Facilitation Effects

In the area of social studies instruction, Guri-Rozenblit (1988a) reported that the addition of a diagram to a text made it easier to remember sequential relationships. Guri-Rozenblit (1988b) also found that diagrams helped in teaching hierarchical relations. Finally, to be most effective, diagrams should not simply be added to text; text should be modified to explain the diagrams.

These two studies demonstrate the typical effectiveness of diagrams in conveying information about spatial relationships (as analogies for abstract relationships) among concepts in sequences and hierarchies. (See Winn and Holliday, 1982, for a review of studies showing facilitation effects for diagrams.) However, information in diagrams is not always encoded spatially (Winn, 1981, 1982; Winn and Sutherland, 1989). I will draw attention to the propositional encoding of certain types of spatial information in a later section discussing maps.

Guri-Rozenblit's work suggests that instructional designers should specifically instruct students how to use diagrams. Simply including them does not guarantee they will be used well, or even used at all. This is a specific instance of the more general principle that students often need prompting and even training to use appropriate learning strategies and materials [see Tobias (1989) for a discussion of the more general issue].

Graphic Organizers

A second way in which visual argument has proven effective is providing students with an organizational structure for content. In three experiments, Jonassen and Hawk (1984) used diagrams illustrating 19th-century industrial growth, Elizabethan theater, and American capitalism as organizers for text passages. The diagrams consisted of labels, boxes, lines, arrows, and other common graphic devices. In each experiment, the immediate posttest performance of subjects seeing the diagrams was significantly better than the performance of subjects in a control group. This suggests a diagram used as an organizer can simultaneously present all of the key ideas, allowing students to construct a schema of what is to follow into which details can subsequently be incorporated without much difficulty.

A number of similar studies of graphic organizers were used by Moore and Readence (1984) in a meta-analysis of this research. Effect sizes were of sufficient magnitude to suggest that graphic organizers can improve recall and comprehension. Interestingly, Moore and Readance found evidence that graphic postorganizers were more effective than graphic organizers placed before instructional content is presented. They suggested that students are more involved with the content by the time they reach the postorganizer, which improves its relevance and effect.

Graphic organizers are one example of advance organizers, the effectiveness of which has long been known (Ausubel, 1968), and which continues to be demonstrated in a variety of contexts (Corkill *et al.*, 1988a,b). Organizers have become an important feature of well-designed instruction. For example, Reigeluth and Stein (1983) include both pre-and postinstructional organizers in their "elaboration theory" of instruction. Finally, this discussion of graphic organizers anticipates a later discussion of text mapping studies, a number of which were included in the Moore and Readence (1984) meta-analysis.

Visualization of Abstract Content

Some of the most difficult abstract concepts for young students to learn come from mathematics. It has long been recognized that diagrams can play an important role in helping children master these concepts (Burton, 1984; Shoenfeld, 1980). Diagrams make the relationships among elements in story problems very concrete and explicit, leading more readily to their solution. Lindvall *et al.* (1982) developed a teaching strategy to help primary-grade children solve a variety of addition and subtraction problems. The strategy required the students to read (or listen to) the story problem, draw a diagram to represent the sets and operations involved, write the corresponding number sentence, and solve the number sentence. The diagrams required students to combine objects into groups ("Ann has three apples. Jill has four apples. How many do they have altogether?"), to separate objects into groups ("Bob and Tony have eight toy cars. Three of them are Bob's. How many does Tony have?"), and to match objects in one group with objects in another ("Jean has five books. Rita has nine books. How many less books does Jean have than Rita?"). Significant gains in performance from pretest to posttest showed this strategy to be effective.

Working with grade four students, Carrier *et al.,* (1985) developed computer lessons using graphics to highlight the structural properties of multiplication and division problems. Problems of the type "5 × 7 = ___?" were illustrated by diagrams. The diagrams showed small pictures of familiar objects arranged in matrices. The number of rows and columns in each matrix corresponded to the numbers that had to be multiplied or divided, so that the 5 × 7 problem had 5 columns and 7 rows of drawings. Subjects who worked with diagrams performed better and remembered more multiplication facts than did subjects who worked with worksheets.

In both of these studies, diagrams made abstract concepts concrete by illustrating very directly the patterns that are so crucial to understanding subjects like mathematics. Spatial visualization is therefore useful beyond the subject of geometry, where spatial relationships, as in the case of maps, are the content itself that must be mastered.

Visualization in Three Dimensions

An extensive program of research into visualization in three dimensions has been carried out in England by Seddon with a number of collaborators. (An interesting characteristic of this research is the diverse cultural backgrounds from which the subjects who take part in the studies are drawn.) As in any work of this kind, the three-dimensionality of the stimuli (in this case diagrams of molecular structure) is most apparent when they are rotated. Rotating three-dimensional diagrams presents the subject with a changing perspective that provides information about how far one object is in front of or behind the others. Seddon's research is therefore concerned with the rotation of diagrams around the vertical and horizontal axes, and around a third axis that is perpendicular to the page or screen.

Most relevant to the current discussion are studies that identified visual cues contributing to the accurate configuration of components in the diagrams. Seddon *et al.* (1984) and Seddon and Eniaiyeju (1986) found that subjects should correctly respond to four such cues to fully understand three-dimensional diagrams. These are: line foreshortening, changing values of angles, relative sizes of parts, and the occlusion of parts by others.

Responding to fewer cues causes decrements in performance proportional to the number of cues overlooked.

Other studies tested instruction that teaches students how to process diagrams of three-dimensional structures. In addition to teaching the four depth cues whose mastery is required for successful performance, the instruction also helped subjects develop skill in rotation and in use of reference frames (Seddon and Shubber, 1985). Comparisons of pre- and posttest performance confirmed that instruction in these skills was effective across a fairly wide age range (13- to 18-year olds). Other studies have shown that instruction using shaded diagrams of rotated models is more effective than using unshaded diagrams (Seddon *et al.*, 1984), presumably because shading is effective in capturing the three-dimensionality of the diagrams, whereas simple projection is not. Also, Seddon and Shubber (1984) found that it was more effective to present diagrams of objects at different rotations simultaneously rather than successively, and that the presence of color improved subjects' learning from the diagrams.

Seddon's research used static views of diagrams at different rotations. The animation of three-dimensional diagrams has also proved a fairly effective instructional device. Zavotka (1987) had university students view animated computer graphics showing objects rotating and changing dimension. This strategy improved their understanding of orthographic drawings. As in Seddon's research, the addition of solid color to the diagram also improved performance. Indeed, subjects were initially confused by rotating wire frame images.

The success of instructional programs for teaching visualization of three-dimensional diagrams is buttressed by the considerable evidence for people's ability to form and rotate mental images. This research was reviewed by Shepard and Cooper (1982). Just as the creation of static mental models involving spatial information improves the understanding of diagrams, the ability to represent and mentally manipulate changing shapes contributes to the understanding of three-dimensional diagrams.

Text Mapping

A good deal of research has shown that using diagrams to capture the structure of text leads to improved comprehension. A number of techniques have been described (Armbruster and Anderson, 1982, 1984; Dansereau *et al.*, 1979; Novak and Gowin, 1984; Schwartz and Raphael, 1985). These techniques illustrated syntactic and semantic relationships spatially on the page. A diagram describing the structure of a text about animals might take the form of a hierarchy with "animal" at the top, "mammal" and "reptile" beneath, and "cat," "dog," "snake" and "lizard" at the bottom. Or it might show a semantic network of nodes and links explicitly illustrated. These techniques have been effective for vocabulary development, pre- and postreading activities, and preparation for writing (Johnson *et al.*, 1986). Improvements in concept acquisition and notetaking for normal and learning-disabled students have also been reported (Bulgren *et al.*, 1988) as have gains in free recall of information in texts (Berkowitz, 1986).

Related research has shown advantages for certain diagramming techniques in the design of computer programs. Diagrams improve performance of novice programmers who receive little other instruction (Isa *et al.*, 1985). Learning how to draw diagrams of program structure also helps students refine specifications of the problems the program is to solve (Dalbey *et al.*, 1986).

Again, in these two lines of research, we find evidence for the advantages of visual argument. It appears that the effectiveness of spatial analogies for describing relationships among abstract concepts, predicted by the theoretical framework, is reliably established.

The Nature of Components

I conclude this section on learning from diagrams with a look at studies that have manipulated how components in diagrams are represented. The theoretical framework suggests that varying the degree of component discriminability affects where attention is directed and what is learned. There is evidence that this is indeed the case.

Holliday *et al.* (1977) compared the effectiveness of two types of flow diagrams that illustrated the water, oxygen, nitrogen, and carbon dioxide cycles. In one version, the components were labeled boxes. In the other, they were labeled drawings. It was found that in a number of recall tasks the diagrams with drawings led to significantly superior performance, but that this effect was limited to low-ability students. A similar finding has been reported in research on mathematics instruction. Moyer *et al.* (1984) found that using realistic drawings of items in word problems, relative to more verbally oriented treatments, improved the performance of low-verbal elementary and middle-school students.

In both of these studies, the criterion for success was performance on tasks requiring processing and recall of the individual components, but not their configuration into clusters. It seems that depicting components realistically provided the support that low-ability students needed to encode and remember them. Holliday *et al.* (1977) interpreted this finding in terms of Paivio's (1971, 1983) "dual coding" theory, which posits that pictures are encoded both imaginally and verbally, whereas words are only encoded verbally. (I return to this idea when I discuss learning from maps.) The additional support provided by redundant imaginal encoding would be helpful to low-ability students but would not be required by high-ability students.

A study by Winn (1982) provided evidence that detail in components makes it easier to remember relationships. Subjects studied diagrams showing the evolution of dinosaurs. In one condition, the evolutionary sequence ran from left to right, as convention would lead one to expect. In another condition, the sequence ran backward, from right to left. Evolutionary sequence was crossed, in a factorial design, with the way in which components were shown, either as drawings or as labels. An interaction indicated that the use of pictures made it easier for subjects who saw "normal" left-to-right diagrams to encode and remember the sequence in which dinosaurs evolved. This difference did not occur for subjects seeing "reversed" diagrams. The direction in which the animals appeared to be walking provided subjects with additional cues on the evolutionary sequence. In the "normal" condition, the dinosaurs appeared to be walking left to right, reinforcing the sequence in which the diagram would normally be read. In the "reversed" sequence, they were walking the other way which would add to the difficulty subjects already had understanding a reversed diagram.

It is clear from these studies that the way in which components are shown can affect both the ease with which details are remembered and, in some cases, the ease with which other tasks are performed as well.

Learning About and From Maps

As previously mentioned, maps differ from diagrams in that they represent real territories in realistic ways. This means that the symbols used in maps represent the world directly, not analogically as is often the case with diagrams. For this reason, developing an understanding of maps and how people learn from them requires different skills than those used when learning from diagrams. The estimation of distances, the interpretation of symbols used in keys, and the literal interpretation of space are examples of such skills. Nonetheless, the general theoretical framework does permit some predictions about understanding maps that the following research addresses and bears out.

The Interplay of Verbal and Spatial Information: Conjoint Retention

The intuition that maps rely heavily on spatial information to convey meaning is, of course, correct. Yet our theoretical background proposes that information in maps and diagrams is encoded in schemata that guide their interpretation. The abstract nature of schemata makes them well-suited for encoding propositional as well as spatial knowledge. This means that information presented in maps can be encoded both spatially and verbally (Schwartz, 1988). There are two bodies of research that address this issue. The first is the work of Kulhavy and his colleagues concerning the "conjoint" encoding and retention of maps. The second deals with the spatial and verbal strategies students use when studying maps.

The basic idea of conjoint retention is not unlike that of Paivio's "dual coding" (Paivio, 1971, 1983). Conjoint retention proposes that verbal and spatial information are stored separately in memory and that separate access to each type of information is available at recall (Kulhavy *et al.*, 1985). This makes it easier to remember both map features and the content of prose passages that describe them. In a study by Schwartz and Kulhavy (1987), subjects read a text organized into episodes while looking at a map that corresponded to the narrative. Some maps were presented in parts that corresponded to the sequence of episodes in the passage, whereas others did not correspond with the passage sequence. Other maps were not broken into parts at all. Congruent maps improved recall, and subjects used spatial information in the maps to improve text recall.

Techniques for improving subjects' conjoint encoding of maps and passages have also been studied. For example, when subjects constructively encode map information both verbally and spatially, the advantages of conjoint retention become even more apparent (Dickson *et al.*, 1988). When subjects produce their own examples of concepts presented in a text and place them on a map, recall of both map and text information improves (Abel and Kulhavy, 1989). The advantages of the *effortful elaboration* (Salomon, 1983) that results when students construct parts of a map seem to apply to conjoint retention as well as to other aspects of learning.

Conjoint retention is influenced by the way components of maps are shown. Amlund *et al.* (1985) observed that when maps are shown as realistic drawings, subjects recall more information than when the components are shown as labels or labeled symbols. Similar results were reported by Kulhavy *et al.* (1983) and by Abel and Kulhavy (1986). It should be noted that Amlund *et al.*'s, (1985) failure to find an interaction between reading ability and the way components were shown is contrary to the interaction reported by Holliday *et al.* (1977) and by Moyer *et al.* (1984) discussed above. In these studies, showing components of diagrams as drawings improved the performance of low-verbal but not high-verbal subjects. Clearly, the relationships among conjoint retention, the way components are shown, and verbal ability are not yet completely established.

It appears from these studies that the verbal and spatial encoding of information presented on maps, and in passages accompanying them, is important for improving recall. If subjects take advantage of the structure maps impose on information, if information on maps is congruent with that in the passages, and if components are shown as recognizable drawings, then conjoint retention is facilitated and more is remembered.

Verbal and Spatial Information: Strategies

A number of studies have examined verbal and spatial strategies subjects use when processing information presented in maps. The successful map reader uses verbal and analytical strategies in addition to spatial strategies. Sholl and Egeth (1982) found that measures of spatial ability were not necessarily good predictors of university undergraduates' map-reading ability. A factor analysis of likely predictors of this skill showed that map-reading ability was determined instead by skill at terrain analysis and altitude estimation. These skills were best predicted by, among other things, vocabulary and mathematical aptitude, respectively.

However, spatial skill plays a natural role in map reading. Thorndyke and Stasz (1980) identified a number of strategies used by expert map readers, including the ability to partition maps into segments, to use mental images, to encode single spatial relations, and to encode patterns of components. Winn and Sutherland (1989) used Thorndyke and Stasz's categories to classify self-reported strategies used by high-school students as they encoded maps. They found that those who used these strategies recalled significantly more information about components and their relative locations.

Thorndyke and Hayes-Roth (1982) looked at the issue of verbal and spatial encoding strategies in a different way. They contrasted learning from maps with learning from navigation through a real environment. From maps, adult subjects constructed mental images that could be scanned in memory in the same way as the maps themselves. [Kosslyn (1986) presents a summary of many studies demonstrating that images can indeed be scanned in this way.] From moving through the environment, people acquired procedural knowledge about how to get from one place to another. Thorndyke and Hayes-Roth provided data showing that learning a route from navigation is more effective than learning it from a map. However, this was only true when exposure to the map or navigation was of relatively short duration. In a related study, Kovach *et al.* (1988) found that undergraduates seeing written instructions were able to drive to a destination in less time than those who saw maps. It appears that propositional encoding of information about how to get somewhere is sometimes more useful than spatial encoding.

Finally, Schwartz and Kulhavy (1988) reported a differential effect on recall of map components by listing them or reconstructing the map as a function of whether subjects were told to encode the features conceptually or spatially. [A similar result was reported by Winn (1988) for diagrams.] Again, this suggests that maps convey different types of information, and that different encoding strategies affect how easy it is to remember them.

The Spatial Properties of Maps

I now move to an examination of research that has addressed how the spatial properties of maps determine the skills necessary for interpretation. The theoretical framework predicts that the configuration of components in maps conveys information important for its own sake because it says something about the territory the map represents. It also predicts that component configuration helps people organize the information itself, regardless of how well it represents the territory.

The importance of spatial skills in learning from maps is supported by research. Bartram (1980) had undergraduates solve problems concerning the most efficient route to take when going from one place to another by bus. Three groups of subjects either studied timetables, street maps with bus routes superimposed, or schematic maps where the routes were shown without extraneous detail. Subjects performed the worst when they saw the timetables, which did not capture any spatial information about the bus routes. The best performance came from subjects who saw the schematic maps, where spatial information was preserved without landmarks and other nonspatial information.

Morrow *et al.* (1987) had undergraduate students read texts describing a person walking through a building after they had memorized a map of the building. From time to time the narrative was interrupted with questions asking where objects were located in the building. Results showed that subjects' responses were more consonant with an understanding of the spatial layout of the building than with the surface structure of the text. Spatial characteristics of the information presented in a map apparently determined people's understanding of it.

In order to determine how the spatial properties of maps affect cognition and interpretation, it is useful to identify cognitive processes used by skilled map readers. The work of Thorndyke and Stasz (1980), described above, is clearly relevant here. But others have also shed light on what good map reading entails.

A study be Streeter and Vitello (1986) suggested a number of skills that good map readers possess. In two experiments, the route selection strategies used by adult subjects were examined as they performed a navigation task. The authors found that navigational proficiency was correlated with spatial ability, and that low-ability subjects tended to rely on landmarks and verbal directions as they navigated through an area. Familiarity with an area also influenced the strategies subjects used. People who knew the area well tended to use a shortest-path breadth-first search strategy, whereas no consistent search strategy was apparent for those unfamiliar with the area.

Work by Gilhooly *et al.* (1988) is also germane. These authors found no differences in measures of attention and retrieval between expert and novice map readers, thus excluding these processes as the key to good map-reading. However, they did find that skilled subjects had developed and used special map-related schemata, whereas unskilled subjects gave more attention to place names when they encoded and recalled information. Moreover, expert map readers remembered more than did novices when they studied topographical maps, but not when they had to learn maps that did not show elevation. This finding is clarified by Kinnear and Wood (1987), who found that topographic maps encourage chunking of contours to form larger features, such as valleys. Expert map readers apparently used such cues as contours to structure the information that maps present, whereas novices do not.

Some studies have correlated map-reading skills with performance on standardized tests of learning style and personality, as well as with gender. In a study involving 14-year-olds, Riding and Boardman (1983) found that field-independent boys performed better on three tests of map reading than field-dependent boys, but that there was no difference for girls. Boys and girls performed comparably on a test of symbol translation. When required to correlate maps with aerial photographs, extrovert boys performed better than extrovert girls. However, on identifying pictures of views from a map, girls performed better than boys. Clearly, this study suggests that map-reading performance depends on relatively complex interactions among a number of personality characteristics, gender, and the nature of the map-reading task.

Some evidence suggest that girls develop visual interpretive skills at an earlier age than boys. Winn and Everett (1979) compared affective ratings to color pictures across gender and at different ages. It was found that children in grade 4 reacted more to the appearance of a picture and that grade 12 subjects reacted to a picture's content. However, performance of grade 8 children, comparable in age to Riding and Boardman's (1983) subjects, was different for boys and girls. The boys still often reacted to the appearance of a picture, the girls to its subject matter. Corroborating evidence with maps is provided by Beatty and Bruellman (1987), who reported that, with older subjects, gender differences for the acquisition of new information from maps were not found, although males appeared to be better at recalling the locations of real places with which they were familiar.

It is possible, however, that map skills are not related to visual skills at all. Landau (1986) reported that a congenitally blind 4-year-old was able to use a simple two-symbol map to guide her movement and find objects in her environment. The author concluded that map-reading skill, though based on spatial ability, is not derived from experience acquired through the operation of vision, which suggests in turn that these skills are independent of sensory modality.

These studies provide evidence that a variety of cognitive skills and strategies are required in learning from maps. Such skills appear to be related to the configuration of map components to create schemata representing the map's meaning. Spatial ability and field-independence are skills that may make this configuration easier to achieve. Likewise, expert map users' special map-related schemata and their ability to use particular map features, such as contour lines, suggest that map reading requires specific as well as general skills and strategies.

Landmarks and Location

As previously mentioned in reference to Sutherland and Winn's (1987) research, the nature of map and diagram components can influence the way in which configurations are learned and recalled. Hardwick *et al.* (1983) suggested there was a direct relationship between the nature of map components and the organization of subjects' internal representations of maps. Undergraduates whose drawings of maps from memory showed they had less well-organized internal representations of a territory tended to select ambiguous features of the territory as landmarks along an unfamiliar route. This suggests the components of a map determine to a considerable extent how well the information is organized spatially and how well subjects navigate and locate themselves.

More explicit examinations of subjects' ability to find routes and locate themselves are found in two other studies. Leiser *et al.* (1987) had undergraduates find routes between points. Half of the subjects studied a map showing all the points simultaneously. The others experienced computer-simulated travel in which only some of the map could be seen at once, but in which subjects had control over which section of the map to see next. The time it took subjects seeing the whole map at once to find routes increased as the distance between the starting point and the destination increased. In the other condition, there was no distance effect. These results indicate that spatial problem-solving is affected by whether subjects attend to the whole map or to only parts of it at a time. The inability to see the big picture does not allow subjects to locate themselves relative to the whole map, and the advantage of seeing the map at a global level is lost.

Peruch *et al.* (1986) found that people use a great variety of spatial strategies to locate themselves on a map. Subjects slid a transparent sheet with the direction of gaze marked on it over the map on which they were to locate themselves. From observations, a variety of behaviors were evident. Subjects either matched internal and external frames of reference, either wholly or in part; or they proceeded in a sequential manner from point to point; or they worked in a random fashion. These data suggest the ability to locate oneself on a map may be influenced by individual differences, a conclusion that is congruent with evidence of other learning style and personality factors affecting map-reading ability described in the previous section.

Distance Estimation

The estimation of distances is a task that relies heavily on how components are represented and arranged on maps. Not surprisingly, more accurate estimates of distances can be made when the map is available for inspection or when actual landscapes are viewed (Bradley and Vido, 1984) than when the map has to be recalled from memory (DaSilva *et al.*, 1987; Kerst *et al.*, 1987).

The accuracy of magnitude estimation depends on whether processing is automatic and on whether the landmarks used for estimating distances are considered pleasant. In the former case, Fisk and Eboch (1989) trained subjects to perform a magnitude-estimation task using color codes that were either consistent or inconsistent across trials. Performance on a transfer task showed that consistent color codes led to faster and less variable performance than inconsistent color codes. This was attributed to the development of automatic processing with consistent codes. In the second case, Smith (1984) reported that distance estimation between landmarks improved when they were judged to be pleasant. Smith proposed that less pleasant landmarks are less prominent, and therefore less useful, than pleasant ones. These two studies suggest the consistency and pleasantness of landmarks affect how well the distances between them are estimated.

Aging

Finally, a number of studies have documented a decrement in map-related spatial skills occurring with age. For free recall of map features, and for recall cued by an outline map, Sharps and Gollin (1988) reported the performance of elderly subjects was significantly lower than that of young adults. This difference disappeared when recall took place in the presence of more distinctive cues on the map. It appears older people require more distinctive cues that induce deeper processing and permit them to recall more details on a map. This finding was confirmed in another study (Gollin and Sharps, 1987), where no differences occurred between young and older subjects' performance on encoding and decoding information presented in maps when the maps contained color or three-dimensional cues.

It seems that age may not affect all processes related to map reading. Thomas (1985) found older subjects recalled fewer landmarks than younger subjects and used different strategies to learn information on maps. However, performance differences do not appear to arise from the way in which context is used by subjects of different ages (Aelinski and Light, 1988).

CONCLUSION

By way of a conclusion, I return to the theoretical framework that was presented at the beginning of the article. I proposed that maps and diagrams were made meaningful by people's configuration of parts into components and components into clusters, and by the discrimination of one component from another. Pre-attentively, configuration is concerned primarily with perceptual organization and structuring what maps and diagrams show. Discrimination has to do with "same" and "different" judgments, and consequently with grouping by form and features. Under the control of top-down processing, configuration has to do with the way in which the relative and absolute placement of components affects meaning. Discrimination leads to the identification of components and what they represent on the basis of their features.

The theoretical framework permits predictions to be made about how well people learn from maps and diagrams. Stated generally, these are: (a) the appropriate exploitation of spatial configurations will lead to better organization and comprehension, especially in the case of people strong in spatial ability; and (b) improving component discriminability in maps and diagrams by varying their features or their familiarity will improve component identification and the comprehension of the map or diagram. The review of research has provided evidence that supports these predictions.

For configuration:

1. Maps and diagrams are well-suited to illustrate intercomponent relationships and sequences. In the case of diagrams, this depends on the analogical use of space to describe relations among abstract ideas, and on certain conventions derived from the traditions of the graphic arts and from the conventions of language. In maps, how spatial relations are conveyed affects such skills as distance estimation and navigation.
2. Graphic organizers provide coherent and concise frameworks into which students can integrate new information, or they can serve to summarize it after the fact.
3. Text mapping techniques in which syntactic and semantic relations are encoded spatially are effective for helping students organize and remember the content of passages.
4. A particular advantage of diagrams is that they make abstract content more concrete and understandable. This is particularly true when teaching mathematics and three-dimensional structures that rotate in space.
5. Subjects with good spatial ability can use those abilities to good advantage when learning from maps and diagrams. There is evidence, however, that some information about the features shown on maps is encoded verbally and through the application of analytical strategies. The effects of learning styles, gender, and aging on map-reading ability also suggest there is no simple relationship between ability and the success of maps and diagrams in instruction.

For discrimination:

6. Conjoint retention enables the establishment of specific structural parallels between maps and written descriptions of territories. The more familiar and the more representative the components are to students, the easier they will be encoded and recalled.
7. Increasing the amount of detail in the components of maps and diagrams affects the precedence of the components. Highly detailed and discriminable components tend to draw attention to themselves and away from the "big picture."

8. The usefulness of landmarks for navigation and distance estimation is improved when they are unambiguous and pleasant to the viewer.
9. The use of notational symbols at the expense of realistic representation improves the usefulness of maps in a number of problem-solving tasks.
10. Color is extremely useful for conveying depth in three-dimensional diagrammatic representations, for cuing, and for use in keys on maps.

This review has presented many other instances where the predictions of the theoretical framework seem to be supported. However, these 10 points illustrate the most frequently supported and the most general predictions. What is perhaps more important is that we can enjoy a certain measure of confidence in the theory underlying the study of maps and diagrams. It is clear that research on human perception and memory is extremely relevant to this endeavor. It is also clear that the theory provides a useful framework within which to conduct future research.

The importance of configuration and discrimination has been demonstrated for both pre-attentive and top-down processing. It will therefore be fruitful for researchers to examine further the role of these in learning from maps and diagrams. Particularly important are studies of precisely how variations in the amount of detail in components affect discrimination. It seems that some variation is necessary, but that too much is self-defeating. Where should the line be drawn? Likewise, we need to discover the optimal intercomponent distances for the formation of unambiguous clusters. How close does one component have to be to another, relative to a third, to be associated with it? At what point do components in a cluster become too close and get confused with each other? Answers to these and other questions will eventually lead to prescriptive principles for the design of maps and diagrams. Better designed instructional materials and greater understanding by students of what they convey will follow.

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