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What Is the Value of Graphical Displays in Learning?

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The article reviews studies that explain the role of graphical displays in learning and synthesizes relevant findings into principles for effective graphical design. Three theoretical perspectives provide the framework that organizes the review: dual coding theory, visual argument, and conjoint retention. The three theories are compatible although they are based on different assumptions. Research suggests that graphics are effective learning tools only when they allow readers to interpret and integrate information with minimum cognitive processing. Learners' characteristics, such as prior subject-matter knowledge, visuospatial ability, and strategies, influence graphic processing and interact with graphical design to mediate its effects. Future research should investigate the interplay between display and learner characteristics and how graphical design can address individual differences in learning from graphics.

KEY WORDS: graphical displays; learning; cognitive processes.

INTRODUCTION

Current technological advances have broadened the range of graphical displays that scientists can use to study phenomena, allowing them to view information in a variety of graphical formats. The assumption underlying efforts to make these representations available to students is that graphical displays can facilitate learning. This review aims to evaluate the above assumption by examining theoretical models of graphic processing. Understanding why and when graphics can contribute to learning may enable researchers

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and educators to develop theory-based principles for their design and instructional use.

Previous reviews concluded that research conducted prior to the 90s had documented the benefits of visual displays but had failed to provide a theoretical framework to explain how graphics benefit learners (e.g., Hegarty *et al.*, 1991; Kozma, 1991; Levin *et al.*, 1987; Winn, 1987). This review of more recent studies shows that during the past decade researchers have gained a better understanding of this process. In addition, findings from this research converge into consistent patterns that show how learner and graphic characteristics may affect learning with graphics.

Three theoretical perspectives that explain the role of graphics in learning have emerged from a review of recent studies: dual coding theory, the visual argument hypothesis, and the conjoint retention hypothesis. All of them are based on information processing approaches to learning, and the assumptions on which they rest are not necessarily in conflict with one another. Their differences arise from their focus on different aspects of graphic processing. Visual argument concentrates on the perceptual and interpretation processes that take place when learners extract meaning from graphical representations. It claims that graphical displays are more effective than text for communicating complex content because processing displays can be less demanding than processing text. On the other hand, both dual coding theory and the conjoint retention hypothesis focus on the memory storage of visual and verbal information. According to these views, the presence of graphics along with text has additive effects on learning because visual information is represented separately from verbal information in long-term memory.

These three theoretical perspectives provide the framework that organizes the literature reviewed in this article. Specifically, each of the three main sections examines: (1) the main assumptions forming the theoretical perspective, (2) the evidence provided by relevant empirical studies, and (3) how research within the perspective addresses the role of learner and display characteristics (see Table I for an overview of the theories). Before addressing the three perspectives, graphic definitions are provided as are the criteria for including the studies reviewed in the article.

Definitions of Graphics

In this article the terms visual displays, graphics, graphical displays, and graphical representations are used interchangeably to characterize displays that represent objects, concepts, and their relations using symbols and their spatial arrangement. According to Bertin (1983), graphics are distinct from other sign systems, such as pictorial representations, because they are

Table I. Summary of Three Theoretical Frameworks on Graphic Processing and Related Research

Theory	Assumptions	Evidence
Dual coding	1. Two different memory representations for verbal and visual information. Connections between them provide two ways to retrieve information 2. Visual representations are organized in a synchronous manner and processed simultaneously, whereas verbal representations are organized hierarchically and processed serially	Neuroscience research provides evidence for the existence of visual memory representations Dual-coding studies provide no evidence for the second assumption that visual representations are processed more efficiently than are linguistic representations
Visual argument	1. Because of their visuospatial properties, graphics are search and computationally efficient	Graphical displays designed using Gestalt principles of perceptual organization are more effective than text in communicating information about data relations, trends, and patterns
Conjoint retention	1. Two different memory representations for verbal and visual information. Connections between them provide two ways to retrieve information 2. Maps are encoded as intact units, and their mental images maintain information on their visuospatial properties	Maps improve memory of text information but there is no evidence from conjoint retention studies for the existence of two memory representations There is evidence for spatial but not *intact* display encoding

monosemic. The elements of monosemic systems have unambiguous and unique meaning because their design relies on predefined conventions. Conversely, pictorial representations, such as paintings, photographs, and drawings, are polysemic because their interpretation involves subjectivity and ambiguity. Goodman (1968) offered a similar categorization of sign systems into notational and nonnotational. In graphics, which are notational, there is a one-to-one correspondence between their elements and their referents, and each element has only one meaning. Photographs and drawings are polysemic or nonnotational because they are not composed of discrete and easily identified elements, and their individual symbols may signify more than one meaning. For example, pictures may be subjected to more than one interpretation (e.g., different viewers may perceive different elements as the background of a picture), and their elements may have multiple meanings (e.g., they may stand as symbols for abstract concepts).

Empirical research supports this broad categorization. It appears that, although all types of displays make use of some common perception and processing mechanisms, interpreting graphical representations requires knowledge of other cultural conventions and, thus, might involve different cognitive processes (Gerber *et al.*, 1995; Mokros and Tinker, 1987). For that reason this article concentrates only on graphics.

One of the challenges in synthesizing research on graphical representations is that there is no standard classification system of graphics and, as a result, the same terms may be used with different meanings from one study to another. For example, Hegarty *et al.* (1991) refer to organization charts and flow charts as diagrams whereas other researchers (Winn, 1987) consider them as types of charts. Another confusion may arise from the fact that different types of graphical displays can be combined into hybrids (e.g., matrices that include both text and iconic symbols), having properties of more than one display (Atkinson *et al.*, 1999).

The review addresses four common types of graphical displays: diagrams, graphs, maps, and (network) charts. Table II explains the similarities and differences among them. Charts are also known as *knowledge* or *semantic maps* (Lambiotte *et al.*, 1989), and when they are used as advance organizers they are also called *graphic organizers*. This categorization of displays was adopted from the work of Lohse *et al.* (1991) who developed a classification system using empirical data on how users classified graphics.

As shown in Table II, diagrams, maps, graphs, and charts use different conventions to communicate information. For example, in diagrams, objects or entities are shown with schematic pictures whereas in charts their elements are typically represented with text enclosed in boxes and circles. There are also differences in the level of abstraction and arbitrariness both across the various types of displays and among displays that belong to the same category. For example, diagrams may differ in terms of their realism, ranging from *iconic*, which represent objects in great amount of detail (i.e., the parts of a microscope), to *schematic* (i.e., the nitrogen cycle; Hegarty *et al.*, 1991). The symbol systems of iconic diagrams and maps are less arbitrary than the ones used in graphs and charts because the distances among the diagram and map elements must correspond to the distances among the entities they represent.

Criteria for Inclusion

Although the review does not aim to be exhaustive, an effort was made to include a large number of studies that are representative of current research on graphical representations. Relevant studies were identified through searches on education and psychology databases (ERIC and PsychInfo) using the keywords *graphical displays* or *diagrams*, and *learning*.

Table II. Taxonomy of Graphics

Graphics	Referents	Symbol system	Characteristics	Some types and examples
Diagrams	Parts, structure, and operation of real objects or abstract entities; processes	Objects and abstract entities are shown by schematic pictures. Relations and sequences are shown with arrows and lines	Nonarbitrary symbol system because parts of the diagrams correspond to the objects or entities they represent. In iconic diagrams the relative distances of their parts correspond to the relative distances of their referents	Iconic (e.g., a diagram showing the operation of a bicycle pump) and schematic (e.g., a diagram illustrating the water cycle)
Maps	Features (or data) and their location (or distribution) in real territory	Arrangement of symbols in a representation of a territory	Nonarbitrary symbol system because the location of map elements correspond to their location in the territory	Geographic maps, route maps (e.g., a subway map), statistical or thematic maps (e.g., weather maps)
Graphs	Quantitative data in a way that enables viewers to compare and observe relations among variables	Line graphs show relations by the shape of the line and bar graphs by the relative size of the bars	Arbitrary symbol system; neither the parts of the display nor their location correspond to the parts and location of their referents	Line graphs, bar graphs, pie charts
Charts	Relations among concepts; sequence of events	Entities and their relations are represented by text, its position, and lines connecting related parts	Arbitrary symbol system; neither the parts of the display nor their location correspond to the parts and location of their referents	Tree diagrams, web-based concept maps, matrices

In addition, more studies were located from (a) the bibliographies of these articles and (b) the tables of content of the journals: *Contemporary Educational Psychology*, *Educational Psychology Review*, *Educational Technology Research and Development*, *Journal of Educational Psychology*, *Journal of the Learning Sciences*, *Educational Psychologist*, and *Learning and Instruction.*

The review focuses only on preconstructed graphics. The reason is that learning with self-generated displays may involve different cognitive processes (Cox, 1999). When students learn from preconstructed displays, they develop their own understanding by internalizing information. On the other hand, when students construct their own representations, they need to develop an understanding of the concepts they study before they can represent their thinking.

The paper concentrates on research published after 1990 because studies conducted before then were included in previous reviews (e.g., Hegarty *et al.*, 1991; Kulhavy *et al.*, 1993a; Lambiotte *et al.*, 1989; Levin and Mayer, 1993; Mayer, 1989a; Rieber, 1990a; Winn, 1991). Thus, findings discussed in older reviews are incorporated without direct reference to the original studies. Exceptions were made for the most influential studies in the field, such as the seminal paper by Larkin and Simon (1987). Finally, studies that had confounded designs or were intended to demonstrate instructional applications of graphics are excluded from this review.

DUAL CODING THEORY AND RELATED RESEARCH

What is Dual Coding Theory?

Dual coding theory (Paivio, 1990) proposes that there are two distinct and independent but interconnected cognitive systems for processing and storing information: an imagery or nonverbal system for nonverbal information and a verbal system for linguistic information. The theory states that the two systems are both functionally and structurally distinct. They are functionally distinct because they process visual and verbal information separately and independently of each other. They are structurally distinct because they store information in representation units that are modality specific, the logogens and the imagens. Both types of representations retain some of the properties of the stimuli and experiences that generated them. Imagens correspond to natural objects whereas logogens are word-like codes. Imagens enable the generation of mental images that resemble the properties of real objects and are amenable to dynamic spatial transformations, which is not possible with verbal representations. Another structural difference between the two types of representations is their organization. Visual information has the advantage that it is organized in a synchronous manner, which allows many parts of a mental image to be available for simultaneous processing. On the other hand, logogens are organized in larger units and in a successive fashion and, hence, they are subject to the constraints of sequential processing, which allows the processing of limited information at a time.

Although the two cognitive systems are functionally distinct, they are interconnected. Associative connections can form between the verbal and visual representations, enabling the transformation of each type of information into the other. For example, people can associate the word book with a picture of a book and, thus, hearing the word book may elicit a mental image of a book.

Paivio and his colleagues claim that dual coding theory has several educational implications (Clark and Paivio, 1991). Illustrations and other visual materials may contribute to the effectiveness of instruction by enabling students to store the same material in two forms of memory representations, linguistic and visual. When verbal and visual information is presented contiguously in time and space it enables learners to form associations between visual and verbal material during encoding. This may increase the number of paths that learners can take to retrieve information because verbal stimuli may activate both verbal and visual representations (Clark and Paivio, 1991). Therefore, including illustrations in text or lectures may support better retention of the material as it provides learners with two ways to memorize information.

Another implication of the theory relates to the finding that people are more likely to remember concrete than abstract information (Paivio *et al.*, 1988; Sadoski *et al.*, 1993). According to Paivio and his colleagues, concrete information is better remembered because it can evoke mental images and, therefore, encourage people to encode the same information in both modalities. Hence another way visual displays may contribute to learning is by increasing the concreteness of instruction when the material is abstract (Clark and Paivio, 1991). Also, providing many visual experiences may enrich students' mental representations and increase their ability to generate mental images when they learn (Clark and Paivio, 1991; Kosslyn, 1988).

Evidence for Dual Coding Theory From Cognitive and Neuroscience Research

The hypothesis that images and verbal information are processed by different systems and stored in different formats has been the focus of debates in psychology and has generated a voluminous body of research over the past three decades. Paivio *et al.* (Paivio, 1983; Paivio *et al.*, 1994; Paivio and Csapo, 1973) conducted several studies to investigate people's memory of visual and verbal information. In a typical experiment (Paivio and Csapo, 1973) participants were asked to memorize lists of words (or sentences) and pictures depicting concrete concepts and to recall them at a later time. A consistent result in these studies was that people had significantly better memory for pictures than for words (Paivio, 1983). Another finding was that exposure to both words and pictures had additive effects on memory, that is, participants who were shown both words and pictures remembered more words than those who only saw words or pictures (Paivio, 1983; Paivio and Csapo, 1973). Such research supported the hypothesis that pictures can improve memory of verbal information.

The assumption that our long-term memory maintains different types of representations for words and pictures has also been addressed in psychological studies that investigated the nature of mental imagery. Mental imagery is the construction of internal images of objects that are not physically present. Kosslyn (1981) has proposed that these "mental pictures" are generated from visual representation units that are stored in long-term memory. Support for this hypothesis was provided by research showing that there are similarities in the way we process physical and mental images (Finke and Shepard, 1986; Reisberg and Heuer, in press). Mental images can be mentally manipulated in the same way we mentally manipulate real pictures (e.g., we can "zoom in" and "out" or "rotate" them). Also, the time required for generating, transforming, and rotating mental images is proportional to their size and characteristics, which is similar to what happens in the processing of external images. Larger mental images take more time to be constructed than small images, and the time required to "scan" or rotate a metal image increases linearly with the amount of distance scanned and the magnitude of the rotation.

Dual coding theory was challenged by psychologists (Johnson-Laird, 1998; Pylyshyn, 1973, 1981) who claimed that at deeper levels of processing both images and verbal information converge to a single, amodal form of knowledge representations. These representations are built from propositions, the smallest linguistic units of knowledge that can stand as separate assertions (Anderson, 1995). According to propositionalists, mental images are constructed from propositional knowledge and not from analog visual representations (Johnson-Laird, 1998).

Current research in psychology and neuroscience has provided psychologists with a better understanding of these issues. First of all, studies on working memory support the assumption that visual and verbal information is processed by two functionally distinct cognitive systems. In the information-processing model, working memory is the central control mechanism of all cognitive activities, whose role is to temporary maintain and process information that we perceive or retrieve from long-term memory. In recent years, some consensus is emerging among researchers in favor of a nonunitary view of working memory (Miyake and Shah, 1999). Specifically, some of the current working memory models propose the existence of domain-specific, separate subsystems for processing visuospatial and verbal information (Miyake and Shah, 1999). For example, the model developed by Baddeley *et al.* (Baddeley and Logie, 1999; Logie, 1995) includes one system for temporary maintenance and manipulation of verbal or auditory information (the "phonological loop") and one that has a similar function for visual material (the *visuospatial sketchpad*). The two systems are controlled by the "central executive," which regulates all processes in working memory. Empirical support for nonunitary models is provided by studies showing that maintaining visuospatial information is affected by concurrent spatial tasks but not by concurrent verbal tasks, and vice versa (Baddeley and Logie, 1999; Robinson and Molina, 2002; Shah and Miyake, 1996).

In addition, studies on brain activity and physiology have shown that manipulation of visual, spatial, and verbal information activates different parts of the brain (D'Esposito *et al.*, 1997; Jonides and Smith, 1997). It also appears that some brain parts are specialized to support depictive representations (Reisberg and Heuer, in press). A critical piece of evidence is that perception and imagery activate the same parts of the brain (D'Esposito *et al.*, 1997). Also, damage to the visual regions of the brain was found to disrupt both perception and imagery. For example, it was found that patients with brain damage who could not see objects to the left side of space had similar problems when they imagined objects (Kosslyn, 1994; Reisberg and Heuer, in press). These studies suggest that there are similarities in how the brain manipulates real and mental images and, therefore, support the hypothesis that mental images are based on visual representation forms. However, research also suggested that visual information may be stored in both visual and verbal representations (propositions). It was found that mental images can be generated by nonvisual brain areas and that people who are congenitally blind can use imagery as an aid to memory although it is unlikely that they can generate it from visual representations (Reisberg and Heuer, in press).

In summary, research in cognitive psychology and neuroscience suggests that people maintain two (or more) distinct cognitive systems for processing verbal and visuospatial information. It also provides evidence for the existence of visual and linguistic forms of representations in long-term memory (although visual representations may be based on both visual and linguistic knowledge units). This evidence supports the assumption of dual coding theory that visual displays can facilitate learning because they enable students to store information in two modalities. However, cognitive and neuroscience studies, including those conducted by Paivio and his associates, involved very simple cognitive tasks and performance outcomes, which severely limits the applications of dual coding theory. For example, experiments required participants to memorize words or pictures depicting simple, concrete objects. The question that arises is whether these findings can be generalized to symbolic representations, learning of content-rich material, and complex cognitive tasks that require integration of multiple information sources.

The next section discusses studies that examined the application of dual coding theory to graphics and to more complex learning tasks that required integration of verbal and visual information.

Evidence for Dual Coding Theory From Research on Graphical Displays

Mayer *et al.* (Mayer, 1989a, 1993; Mayer and Anderson, 1992; Mayer and Gallini, 1990) investigated the applications of dual coding theory to the design of explanatory diagrams for science learning. A summary of this research (display types, instructional conditions, measures, and main findings) is presented in Table III. The studies focused on scientific text and diagrams (line drawings that were either static and embedded in text or animated and presented on a computer screen along with text or narration) intended for undergraduate students with low subject matter knowledge. The materials explained the workings of various mechanical devices or processes in science phenomena such as lightning. For example, the diagrams showed physical systems and how changes in one part of the system related to the behavior of its other components. The purpose of the materials was to help students develop coherent mental models of these science processes. The researchers explored the characteristics of effective diagrams and the role of individual differences in learning from diagrams. Learning was assessed in terms of students' information recall and their ability to use new information in problem solving.

Research on the role of graphical design in learning with diagrams was also conducted by Rieber (1990b, 1991a,b). In his studies diagrams were used in computer-based instruction intended to help elementary school children learn about Newton's laws of motion (see Table III).

Two other sets of studies examined the cognitive processes in learning with text and diagrams. These studies did not aim to evaluate the assumptions of dual coding theory but are included in this section because their findings are relevant. One body of research includes the studies by Sweller and his colleagues, which are based on cognitive load theory (Sweller *et al.*, 1998). The other set of studies are those conducted by Hegarty and her colleagues on how readers integrate information from text and diagrams.

Table III. Summary of Dual Coding Studies

Study	Displays	Participants	Learning outcomes	Instructional conditions	Findings
Mayer (1989a,b)	Explanative text illustrations (depicting a brake system) with and without labels	College students	1) Recall of explanative information 2) Problem solving—applying explanative information	Students learned about mechanical systems from explanative text with or without illustrations	Only labeled illustrations improved learning of explanative information and problem solving
Mayer and Gallini (1990)	Explanative text illustrations (brake and pump systems) and nonexplanative illustrations (parts of system or steps of the process)	College students	(Same as above)	Students learned about mechanical systems from explanative text with explanative or nonexplanative illustrations	Explanative illustrations were more effective than were nonexplanative illustrations. They improved conceptual learning and problem solving for low- but not for high-knowledge students
Mayer and Anderson (1991)	Animated diagrams (showing how bicycle tire pump works) accompanied by narration	College students	(Same as above)	Students received simultaneous or successive presentations of animated diagrams and auditory explanative information	Simultaneous presentation of visual and auditory information resulted in better problem solving but recall of explanative information was the same for all conditions
Mayer and Anderson (1992)	Animated diagrams (showing the working of bicycle tire pumps and car brakes) and narration	College students	(Same as above)	(Same as above)	No difference between groups in retention of explanations but the concurrent presentation had a positive effect on problem solving

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Table III. (*Continued*)

Study	Displays	Participants	Learning outcomes	Instructional conditions	Findings
Mayer and Sims (1994)	Animated diagrams (bicycle tire pumps and human respiratory system) accompanied by narration	College students	Problem solving—applying explanative information provided in the instruction	(Same as above)	Concurrent presentation had a positive effect on problem solving However, it benefited more high- than low-spatial-ability students
Mayer *et al.* (1995)	Explanative text illustrations (showing the process of lightning) accompanied by text	College students	Problem solving—applying explanative information provided in the instruction	Students learned about lightning from explanative text with illustrations presented either coordinated with or separated from the text	Concurrent presentation had a positive effect on problem solving
Mayer *et al.* (1996)	Explanative text illustrations (showing the process of lightning) accompanied by text	College students	1) Recall of explanative information 2) Problem solving—applying explanative information provided in instruction	Students learned about how lightning works from explanative text (full passage or summary) with or without illustrations	Short explanative texts (presenting major steps in a scientific process) are more effective for the retention and transfer of explanative information than are longer texts but only when coordinated with visual information
Mayer and Moreno (1998)	Animated diagrams (showing the process of lightning	College students	1) Recall of explanative information	Students viewed a computer animation showing the process	The effectiveness of multimedia presentations

	and the workings of car brakes) with concurrent narration or on-screen text		2) Recall of illustration elements 3) Problem solving—applying explanative information provided in instruction	of lightning concurrently with either a narration or on-screen text	increases when verbal and visual information is presented in separate modalities (animation with narration)
Moreno and Mayer (1999)	Animated diagrams (showing the process of lightning) with concurrent narration or on-screen text (which was integrated with or separated from the diagrams)	College students	1) Recall of explanative information 2) Recall of illustration elements 3) Problem solving—applying explanative information provided in instruction	Students viewed a computer animation showing the process of lightning concurrently with either a narration or two types of on-screen text	The effectiveness of multimedia presentations increases when verbal and visual information is presented in separate modalities (animation with narration) and when it is temporally and spatially coordinated
Rieber (1990a,b)	Computer-based, interactive animated diagrams or static diagrams (displaying motion and trajectory with lines and arrows) that simulated Newton's laws of motion	Fourth- and fifth-grade students	1) Intentional learning of scientific principles (Newton's 1st law) 2) Incidental learning of scientific principles (Newton's 2nd law) that were not explicitly taught but could be inferred from the animation	Computer-based instruction including text only or text and (either static or animated) graphics, with or without practice activities	Students who used the animated graphics scored higher on both outcomes but only when they were provided with guidance (practice) Static displays did not improve learning as compared to text alone

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Table III. (*Continued*)

Study	Displays	Participants	Learning outcomes	Instructional conditions	Findings
Rieber (1991a)	(Same as above)	Fourth-grade students	(Same as above)	Computer-based instruction including text and (either static or animated) graphics. Two types of practice activities were provided: structured simulation and multiple-choice questions	Animated graphics were more effective for both intentional and incidental learning. Animated graphics students made inaccurate interpretations of incidentally presented scientific principles
Rieber (1991b)	(Same as above)	Fourth-grade students	(Same as above)	Computer-based instruction including text and either static or animated graphics presented either in chunks of information units or as large continuous units	Students who used the animated graphics scored higher than did the static graphics group but only when the information was provided in small chunks that cued students to details in the visuals. Also, the animated graphics promoted incidental learning

In general, research has shown that diagrams can provide a valuable contribution to students' learning but their effects are contingent upon two important factors: the characteristics of the displays themselves and the characteristics of the learners who use them.

Display Characteristics

Displays Need to Address the Goal of the Task. As Levin *et al.* (1987) noted in an earlier review, only some displays are good for learning. The studies reviewed here showed that displays must meet the demands of the learning tasks in order to be effective. For example, when the goal is to help students understand cause–effect relations or how systems behave, diagrams need to show not only the components of the systems but also how they interact and interrelate (Mayer and Gallini, 1990). When the task involves learning about dynamic phenomena, animated diagrams might be better than static displays because they depict motion and trajectory more effectively (Rieber, 1990b).

Displays Should be Provided Along With Explanations and Guidance. In his studies, Paivio (1983) found that pictures were more effective than were words in helping people memorize lists of objects. Does this hold in contexts when people have to learn more complex material? The studies reviewed in this section showed that, adding visual displays to verbal material can enhance student understanding but displays are not effective when used without guidance or explanations. Rieber (1991a) found that students often do not know what information they need to observe in a display, and they are likely to draw wrong conclusions from what they see. In his studies, graphics contributed to learning when students were guided by questions for practice or prompts that encouraged interaction with the displays (Rieber, 1990b). Such techniques may cue attention to relevant details.

Displays Need to be Spatially and Timely Coordinated With Text. Dual coding theory predicts that providing material in both visual and verbal format enhances learning (Clark and Paivio, 1991). The studies by Mayer and colleagues showed that visual displays must be provided in spatial and timely coordination with the verbal information in order to be effective. In other words, visual displays have to be spatially close (Mayer *et al.*, 1995; Moreno and Mayer, 1999) or presented simultaneously with verbal information (Mayer, 1994; Mayer *et al.*, 1996; Mayer and Anderson, 1991, 1992). Mayer and Anderson (1992) called this effect the *contiguity principle.* Concurrent use of verbal and visual material can help learners develop richer and more coherent mental models because they can form connections between what is presented in graphics and text. On the other hand, when visual and verbal information is presented separately, learners are less likely to integrate the material. With separate presentations, learners have to read some portion of the text and then maintain it in their working memory while attending to the display (Moreno and Mayer, 1999). This places higher cognitive demands on working memory and increases the possibility that, because of working memory limitations, some information will be lost or remain unintegrated.

The effectiveness of the contiguity principle depends on the modality in which new information is presented. Mayer and Moreno (1998; Moreno and Mayer, 1999) found that learning is better when students receive verbal information from an auditory narration than from text. Their results are consistent with the dual coding model, which states that visual and verbal stimuli are processed independently. When verbal information is provided through text, it is initially processed by the visual system. Therefore, presenting verbal and visual material in the same modality (e.g., using text instead of narration) increases the processing demands on the same system. Same modality presentations minimize the benefits of the displays because they leave fewer cognitive resources for integrating visual and verbal information. On the other hand, simultaneous use of images and auditory narration enables learners to build connections without overloading their working memory (Mayer and Moreno, 1998; Moreno and Mayer, 1999).

The above findings are consistent with the research of Sweller and his colleagues, which is based on cognitive load theory (Sweller *et al.*, 1998). The theory proposes that learning difficulty may sometimes result from the design of instruction and not from the nature of the material to be learned. Some instructional procedures may impose a heavy extraneous cognitive load that interferes with learning. In particular, tasks that require learners to associate and mentally integrate multiple pieces of information place high cognitive demands on working memory, especially when this information comes from more than one resource.

Sweller and his colleagues did several experiments in which students used instructional materials that involved text and displays, such as technical diagrams (Sweller and Chandler, 1994), cross sections of geographic maps (Purnell *et al.*, 1991), and geometry diagrams (Mousavi *et al.*, 1995). In the studies, materials in which visual and verbal information was physically integrated (e.g., descriptors were embedded in the diagrams) were compared to materials in which segments of information (e.g., a diagram and explanatory text) were separated. The researchers investigated the role of these two types of materials in a variety of tasks, such as geometry problem solving, factual learning, or learning about equipment operation. Also, a variety of measures were used to assess students' performance, such as time on task, problem-solving performance (e.g., errors or number of correct steps used in solution), and memory of facts. The studies showed that integrated materials were more effective than nonintegrated materials. Nonintegrated materials placed an extraneous cognitive load on students' learning of new content and their problem-solving performance, because the materials required students to split their attention among the different sources of information (text and diagrams). However, displays should integrate only those pieces of information that are unintelligible until mentally integrated, and not segments that can be understood in isolation, because cognitive load may also be produced when students are asked to process redundant information (*redundancy effect*; Sweller *et al.*, 1990; Sweller and Chandler, 1994).

Learner Characteristics

Content Knowledge. It appears that learners' prior knowledge mediates the effects of explanative diagrams but its role is not straightforward. Mayer and Gallini (1990) found that students with low prior knowledge about mechanical devices benefited more from the diagrams than high-knowledge students. However, the research of Hegarty *et al.* (1991; Hegarty and Just, 1989, 1993) provided a different perspective. The Hegarty *et al.* studies focused on similar graphical displays (iconic diagrams showing the components and configuration of mechanical devices such as pulley and gear systems) but used a different methodology. The researchers collected data on readers' eye-fixations, which enabled them to gain a detailed record of how readers processed text and diagrams to construct mental models of mechanical systems. Analysis of their reading behavior showed that readers constructed their mental representations of the material incrementally and by integrating information from both media (Hegarty *et al.*, 1991; Hegarty and Just, 1989, 1993). Viewers tended to switch between text and diagram several times. After reading a unit of text describing the relations between a few system components, they turned to the diagram to elaborate and clarify their understanding of the system sections described in the text. In addition to these *local* diagram inspections that helped them develop representations of smaller sections of the system, at the end of their text reading participants made *global* inspections, that were longer and focused on many components, so as to combine local representations into an understanding of the whole system (Hegarty and Just, 1989, 1993).

In their studies, Hegarty and colleagues found that individual differences in prior knowledge affected comprehension and the quality of readers' understanding. High-knowledge participants were more capable of locating the relevant information in a diagram and extracted information more selectively (Hegarty and Just, 1989). Also, they were able to form a representation of the system even when the text did not provide all the relevant information. In contrast, low-knowledge readers did not know what parts of the system were relevant to its functioning and could not develop a representation of the system from the diagram alone (Hegarty and Just, 1989, 1993). Rather, they needed direction from the text to locate and encode information from the diagram (Hegarty and Just, 1989). Another difference was that low-knowledge readers had more difficulty in comprehending parts of the system and integrating information from the text and the diagram (Hegarty and Just, 1993). As one may expect, high-knowledge readers had superior comprehension of the configuration of system components and developed a better understanding of their movement (Hegarty and Just, 1993).

The above studies showed that high prior knowledge enabled readers to make more strategic use of text and diagrams and to integrate information successfully from the two sources using less mental effort. This finding is different from the conclusion drawn by Mayer and Gallini (1990) who found that high-knowledge students did not benefit from the use of diagrams. The discrepancy in the findings between the two sets of studies may have to do with how they assessed prior knowledge. In the Hegarty and Just studies (Hegarty and Just, 1989, 1993) students' prior knowledge was assessed with a test measuring general knowledge of mechanical systems. In the Mayer and Gallini (1990) study, the prior-knowledge measure was more specific to the content of the diagrams. It is likely that, on the one hand, students need to have a minimum of prior knowledge or some general relevant knowledge in order to interpret and integrate the information provided in diagrams but, on the other hand, they may benefit more when their knowledge is not too advanced. Another explanation for the results of the above studies is that the learning effects of diagrams may be a function of the interaction of their characteristics and learners' prior knowledge. Mayer and Gallini (1990) used a series of diagrams that separately depicted parts of the mechanical process, whereas in the studies of Hegarty and her colleagues students were provided with a single diagram containing all the information. It is possible that such complex diagrams are effective for high-knowledge students whereas low-knowledge students benefit more from diagrams that present less information and present it in a progressive manner. These are all hypothesis that require investigation in future studies.

Visuospatial Ability. Visuospatial ability is the ability to mentally generate and transform images of objects and to reason using these imagery transformations (Carroll, 1993). Although research suggests that visuospatial ability influences graphic processing, understanding of its role is limited.

Mayer and Sims (1994) found that diagrams had a lower effect on students with low spatial ability. The authors speculated that visual displays require low-ability students to devote more cognitive resources for the construction of a visual representation in working memory, which reduces the recourses they can allocate for building connections between verbal and visual information. It appears that diagrams may be more demanding to process, and thus less beneficial, when students do not have high visuospatial ability.

Discussion

Dual coding theory claims that visual displays can contribute to learning for two reasons. One reason is the existence of two different types of representations in long-term memory. According to the theory, storing information in two codes, linguistic and visual, may increase memory of that information because it provides two paths to retrieve it from long-term memory. The other reason is the structural characteristics of visual memory representations. Dual coding theory claims that visual representations can be accessed as a whole and processed in a simultaneous manner, whereas linguistic representations are hierarchically organized and processed sequentially, one piece of information at a time. It is likely that graphics can improve our memory of verbal material because, owing to working-memory limitations, their mental reconstruction allows faster and more effective processing than does verbal representations.

The first assumption, that human cognition is specialized for processing and representing verbal and visual information, has received empirical support from research in cognitive psychology and neuroscience. However, dual coding theory does not address some critical issues that concern the way learners integrate verbal and visual information, which are still under investigation in psychology. One such issue is that the theory (and existing models of working memory) cannot adequately explain how the two (or more) separate cognitive systems work together (Miyake and Shah, 1999). Little is known about how people can coordinate complex cognitive tasks that simultaneously involve both systems and that require integration of different types of information. Second, there is no consensus among researchers on the number of cognitive systems, their limitations, and the nature of information and tasks for which they are specialized. And, finally, it is not clear how individual differences in working memory capacity(ies) and visuospatial ability affect performance in complex tasks that require integration of verbal and nonverbal information (Miyake and Shah, 1999).

Gaining an understanding of these issues has both theoretical and practical importance. Knowing more about the functions, limitations, and coordination of the various cognitive systems may clarify how learners integrate information from different media, and clarify when these media facilitate learning or compete with each other for learners' cognitive resources. The research on graphics presented previously showed that, although visual displays can contribute to learning, acquiring and integrating information from two sources is itself a highly demanding cognitive task. Depending on how the materials are designed (modality and coordination), attending to two types of representations may either improve understanding of the material or interfere with the learning process by imposing an extraneous cognitive load. One important design principle is what Mayer and Gallini (1992) called the contiguity principle: in order to minimize the cognitive load associated with mental integration of information, new material should be provided in different modalities and coordinated in space and time.

Another important research finding is that graphical displays do not benefit all types of learners in the same way; rather, their effect is a function of learners' visuospatial ability and content knowledge. Learners with low visuospatial ability are likely to experience difficulties in processing visual information and therefore may not benefit from graphical representations. An important question for future research is how to address the difficulties of these students through appropriate graphical design and learning materials. Prior knowledge is another factor that mediates the effects of visual displays. Learners with high prior knowledge tend to be more strategic and can integrate visual and verbal information more successfully and with less mental effort. This suggests that, because of the difficulties associated with information integration, the design of instructional materials should compensate for low-knowledge readers' lack of strategies. The studies reviewed here show that this can be accomplished by breaking down the information in multiple displays and by using cues (such as arrows or descriptors embedded in the display) and labels that direct readers to the parts of the display that are important.

As discussed previously, dual coding theory attributes the advantages of visual displays to two factors: to the existence of two representation codes in long-term memory and to the structural characteristics of visual displays. However, findings from Paivio's studies and from research on diagrams do not enable researchers to conclude whether both factors or only one of them is responsible for the effects of visual displays. An alternative interpretation of the studies by Mayer and his colleagues is that diagrams facilitated learning because, by communicating some of the text information visually, they involved the visual cognitive system (the visuospatial sketchpad), and thereby reduced the cognitive load that was required for text processing (Robinson and Molina, 2002). The same findings can also be used to argue that visual displays can enhance learning from text because they communicate information more effectively and impose low demands on working memory, and not because they are stored separately from text in long-term memory. This hypothesis was investigated by another research paradigm—the visual argument hypothesis—which is examined next.

THE VISUAL ARGUMENT HYPOTHESIS

What is the Visual Argument Hypothesis?

"Visual argument" is a term introduced by Waller (1981) to characterize the way graphics communicate information. According to the visual argument hypothesis, graphical representations are effective because, owing to their visuospatial properties, their processing requires fewer cognitive transformations than does text processing and does not exceed the limitations of working memory. Specifically, it has been argued that diagrams, maps, charts, and graphs communicate information through both their individual elements and the way their elements are arranged in space. This phenomenon, also known as *perceptual enhancement* (Larkin and Simon, 1987), makes graphical displays effective for communicating information about both individual elements and their relations, making it easier for users to perceive or draw inferences about these relations than does text (Robinson and Kiewra, 1995; Winn, 1991).

According to Tversky (2001, 1995), many of the conventions used in graphical representations today originated in visual perception and interpretation biases. This belief is supported by strong similarities in the development of graphic conventions in various cultures. Also, there are correspondences between these conventions and certain language expressions or physical analogs, as well as similarities in how language and graphical representations use space (Tversky, 2001, 1995). For example, graphics express increase or improvement with upward movement or direction, which is also true for the concepts "more" or "better." In both language and graphics, space is used to separate and to group elements. In graphics, elements that are spatially close are perceived as group members whereas in language, space separates words and paragraphs. Finally, some conventions seem to be based on physical analogs. For example, arrows, which were invented for hunting, have been adopted in graphics to express movement and directionality in space and time (Tversky, 2001).

Larkin and Simon (1987) developed production system models to understand the cognitive mechanisms underlying graphic processing. According to their models, diagrams provide a "computational advantage" compared to text because they support information search and enable viewers to extract information by relying on automatic, perceptual processes. Using text during problem solving requires that users search the entire text for relevant information and then store it in working memory while searching for the next relevant piece. This continues until all relevant information has been located and draws heavily on working memory resources. This process is prone to error because working memory has limited capacity and cannot maintain data for a long time without constant attention. On the other hand, graphical displays organize information spatially. When all the important information is grouped together in a display, it can be easily located. Users do not have to store any data in working memory because the necessary data are always available in the display and are easily retrieved.

According to the framework proposed by Larkin and Simon (1987), an additional reason why graphical representations are computationally efficient is that they enable viewers to make "perceptual inferences," to extract information automatically using their perception mechanisms instead of engaging in interpretation processes. For example, viewers can make quick and easy judgments about differences in the magnitude or sizes of diagram entities by the relative sizes of the elements (e.g., length of lines) that represent them. These two characteristics of graphical representations make them easier to process than text.

More recent work in cognitive science and artificial intelligence (Scaife and Rogers, 1996) has further explored the role of symbolic visualizations in reasoning and problem solving and extended the framework proposed by Larkin and Simon (1987). Although this work studied diagrammatic reasoning in the domain of logic or involved simple tasks (e.g., Tic-Tac-Toe), its implications are relevant to the role of graphical representations in more complex tasks and to reasoning in other domains. This research suggests that graphical displays, because of their computational efficiency, play a critical role in several cognitive tasks. Rather than simply providing information, visual displays can influence the nature of cognitive activity and operate as "external cognition" (Scaife and Rogers, 1996) by guiding, constraining, and facilitating cognitive behavior (Zhang, 1997). When people reason about a problem using symbolic representations they do not have to mentally carry out all the thinking processes but, instead, they can think of a solution by manipulating parts of visual images. Reasoning often requires consideration and evaluation of alternative possibilities. When diagrams make these alternative states explicit to the viewers, they direct them to certain solution paths (Bauer and Johnson-Laird, 1993). Diagrams may also facilitate problem solving if their design enables them to represent some of the rules that people would otherwise have to maintain in working memory while reasoning about the problem (Zhang and Norman, 1994). This representation reduces memory load and makes more cognitive resources available for planning and other processes. Displays are more effective if they allow viewers to extract information (e.g., problem rules) through direct perception without engaging in deep processing (Zhang and Norman, 1994). Finally, graphical displays may support reasoning during problem solving because their elements may trigger the recall of relevant knowledge, which may facilitate solution-leading inferences (Narayanan *et al.*, 1995).

In summary, according to the visual argument perspective, symbolic representations can be processed more efficiently than text, which allows them to support cognition in complex tasks. They can function as memory aids, enabling viewers to have access to information without maintaining it in working memory, guide cognitive activity, and facilitate inferencing during problem solving.

Research Evidence for the Visual Argument Hypothesis

Two groups of studies addressed the visual argument hypothesis. One group used graphic organizers to examine whether visual displays help students learn concept relations. The second group used a larger variety of displays, such as diagrams and line graphs, to investigate how users search and interpret graphics. Summaries of these studies are presented in Table IV.

Research on Concept Learning Using Graphic Organizers

Research on the role of graphics in concept learning focused on graphic organizers that were used as adjunct displays. Graphic organizers descended from Ausubel's advance organizers (Ausubel, 1960), which were designed to serve as overviews of new material so as to facilitate connections between new ideas and learners' prior knowledge. However, graphic organizers do not simply represent an overview of new material but make use of a spatial format to also communicate information about concept relationships. Graphic organizers can be used in a variety of ways, ranging from adjunct displays, representing portions of text information, to student-constructed displays used as note-taking devices or problem-solving tools.

In the present review, the term graphic organizer is used to include all types of text-based displays such as tree diagrams, matrices (Robinson and Schraw, 1994), and concept maps (Novak, 1996). The various types of graphic organizers differ in terms of how they use space to represent content (Robinson and Kiewra, 1995). For example, some graphic organizers depict only hierarchical concept relations (e.g., concept maps and tree diagrams) whereas others present multiple relationships at the same time using nodes

Table IV. Summary of Visual Argument Studies

Study	Displays	Participants	Learning outcomes	Instructional conditions	Findings
Winn *et al.* (1991)	Tree diagrams	Graduate students	Response latencies (time needed to solve each problem)	Students were asked to solve kinship problems using either tree diagrams or lists of sentences	Students took less time when using diagrams but this effect disappeared when students were not familiar with the conventions and terms of the content of diagrams
Wiegman *et al.* (1992)	Network charts (knowledge maps)	College students	Concept and factual learning: 1. Fill-in the-blank 2. Multiple choice Tests assessed recall of information presented in knowledge maps	Students studied different types of knowledge maps: web-configured vs. map structured using Gestalt principles; stacked vs. whole maps; maps with simple lines vs. maps with links explaining relationships (embellished)	1. Maps configured using Gestalt principles were more effective than web-like maps 2. Stacked maps were more effective for high-spatial-ability students and whole maps for low-spatial-ability students 3. Maps with embellished links were more effective for high-verbal-ability students
O'Donnell (1993)	Network charts (knowledge maps)	College students	Search for different types of information in knowledge maps and text	Students used either knowledge maps or text to search for five different types of information	Knowledge maps were easier to search than text but only for declarative questions and not for questions that required integration and inferences Students with high prior knowledge and vocabulary performed better in both conditions
Guthrie *et al.* (1993)	Bar graphs and iconic diagrams	College students	Search for different types of information in bar graphs, iconic diagrams, and text	Students were asked to search for facts (local search) or for information that required inferences (global search) in bar graphs, diagrams, and text	Students performed better on local than on global search tasks

Robinson and Schraw (1994)	Network charts/graphic organizers (matrices) and outlines	College students	Memory of patterns and concept relations: true-false test items	Students studied either an outline or a matrix after studying text	Matrices were more effective in helping students learn concept relationships; however, their effects disappeared when testing was delayed
Robinson and Kiewra (1995)	Network charts/graphic organizers (tree diagram and matrices) and outlines	College students	Conceptual and factual knowledge: 1. Multiple-choice 2. Hierarchical relations test 3. Essay assessing understanding of concept relations	Students studied text using either matrices or outlines. They were tested 1 and 2 days after the study	Matrices were more effective than were outlines in helping students learn concept relations and applying their knowledge. Effects were maximized when students were given enough study time and decreased less than the outline effect with delayed testing. The groups did not differ in factual learning
Shah and Carpenter (1995)	Line graphs representing data for three variables	College and graduate students	Comprehension of data presented in graphs	Students were asked to describe and compare data (relations and values) presented in various line graphs	Students understood the x–y relations but did not encode the z–y relations Graduate students (experts) demonstrated the same difficulty
Robinson and Skinner (1996)	Network charts/graphic organizers (matrices) and outlines	College students	Response time and number of errors	Students had to locate facts (local searches) or make concept comparisons (global searches) in matrices, outline, or text	Matrices and outlines were more effective than were text in local searches. Matrices were more effective than outlines in global searches but did not differ in local searches

(*Continued*)

Table IV. (*Continued*)

Study	Displays	Participants	Learning outcomes	Instructional conditions	Findings
Robinson *et al.*, (1998)	Network charts/graphic organizers (matrices) and outlines	College students	Application of concepts to new situations	Students used matrices or outlines as review materials after studying text. A control group used text alone	Graphic organizers were more effective as review materials when the review was delayed because students tended to use nonmemorization strategies. When review was immediate after study, students used memorization strategies
Atkinson *et al.* (1999)	Mnemonic pictures and three versions of outlines and matrices: verbal, conventional pictorial, and pictorial-mnemonic (e.g., matrix elements resembled objects)	1. College students 2. Elementary school students	1. Factual learning 2. Concept learning 3. Application	Students studied matrices or outlines after studying text	Mnemonic pictures either in matrices or alone were more effective than were conventional pictures and outlines. The matrix format had only limited positive effects on learning from text. Matrices were effective when they were *localized*, enabling readers to perceive relationships easily
Shah *et al.* (1999)	Line and bar graphs	College students	Comprehension of line and bar graphs	Students were asked to describe the data presented in graphs	Students' descriptions were influenced by graph format. Students comprehended graph information when it was available in visual chunks which enabled them to associate it to its quantitative referents

and links (e.g., web-based knowledge maps). Finally, other graphic organizers (e.g., matrices) provide information on both hierarchical relations and comparisons among concepts along attribute values.

Research prior to the 90s failed to reach conclusions on the learning effects of preconstructed graphic organizers. Some studies favored graphic organizers (Hawk, 1986; Kenny, 1995; Kiewra *et al.*, 1988; Willerman and Harg, 1991) whereas others showed no significant or limited effects (Rewey *et al.*, 1991; Simmons, 1988). As noted in previous reviews (Dunston, 1992; Lambiotte *et al.*, 1989; Rice, 1994; Robinson, 1998), a significant limitation of this research is that, although it examined the effectiveness of graphic organizers in a wide variety of settings, it did not study the factors that make these displays effective tools and it measured learning mainly with factual tests.

Recent research shows that the advantage of graphic organizers over text or linear, nongraphic displays (e.g., outlines) relies on the quality of information they communicate. Although graphic organizers may convey factual information as well as text or linear displays do, graphic organizers are more effective than text in helping readers make complex inferences and integrate the information they provide. This was shown in a series of studies conducted by Robinson *et al.* (1998; Robinson and Kiewra, 1995; Robinson and Schraw, 1994; Robinson and Skinner, 1996) who compared the effects of outlines and matrices on concept learning. In their studies, college students used matrices and outlines as study aids after reading science and psychology texts. Learning was measured not only with factual tests but also with concept relation and transfer tests. The researchers found that although there were no differences between outlines and matrices in terms of factual learning, matrices were more effective than outlines or plain text in helping students identify patterns among concepts (Robinson and Schraw, 1994) and integrate new concepts (Robinson and Kiewra, 1995). These effects on student learning were statistically significant when experimental conditions paralleled classroom learning conditions, involving the use of long texts, multiple organizers, and sufficient to study time (Robinson and Kiewra, 1995). In addition, students benefited from matrices when they used them after text reading (Robinson and Kiewra, 1995) or as a review of material they had studied a few days earlier. When used for review, graphic organizers encouraged learners to use nonmemorization strategies and to focus on concept relations (Robinson *et al.*, 1998).

Furthermore, recent research shows that not all text-based displays are effective. Rather, to communicate a visual argument, displays should be designed in ways that facilitate their processing and that allow viewers to easily perceive the relations they are meant to communicate. This was shown in a study by Wiegmann *et al.* (1992) who compared knowledge maps that differed in their structural characteristics. The researchers found that knowledge maps that were configured using Gestalt principles of organization (e.g., using proximity and clustering) were more effective than were web-configured knowledge maps in helping students learn concept relations. This study also suggested that large and complex knowledge maps hindered performance in some students. This finding is consistent with that of Atkinson *et al.* (1999) who found that matrices that did not organize important information in clusters and, therefore, did not enable readers to perceive important concept relations at a glance provided little or no advantage over outlines or text.

In summary, research has shown that visual displays whose spatial structure facilitates comparison among their elements can help learners easily perceive relations in these elements. In addition, displays should make concept or object relations salient without overwhelming learners with more information than they can process at a time.

Research on Information Search Using Graphic Organizers, Diagrams, and Graphs

Display Characteristics. According to the visual argument perspective, the advantage of graphical displays, relative to text, is their search and computational efficiency. This means that by placing related objects or concepts close together graphical displays enable learners to easily locate various pieces of information (Larkin and Simon, 1987). Also, displays support thinking during problem solving because they reduce the amount of information that must be maintained in working memory.

Research has provided support for this hypothesis. For example, Winn *et al.* (1991) found that tree diagrams were effective for helping people draw inferences about relations. The researchers asked graduate students to solve kinship problems using either tree diagrams (family trees) or lists of statements. Winn *et al.* (1991) found that students who used tree diagrams took significantly less time to solve the problems. This finding indicated that tree diagrams required less searching. Similarly, Robinson and Skinner (1996) compared matrices and outlines containing equal numbers of words and found that students who used matrices took less time to both locate pieces of information (individual concepts) and to "compute" information—compare and identify patterns among these concepts (Robinson and Skinner, 1996).

Although displays facilitate information search, locating and comparing individual data values is typically easier than complex inference making. Viewers are not always successful in tasks that require them to interpret relations, trends, and patterns in the data. O'Donnell (1993) found that knowledge maps were more effective than text in helping students locate factual information but knowledge maps and text were equally effective for answering questions requiring information integration and inference-making. Similarly, Guthrie *et al.* (1993), who collected think-aloud data to study how undergraduate students searched bar graphs and iconic diagrams, found that with both types of displays *global* search tasks—finding relationships and detecting patterns—were more difficult than *local* search tasks—locating individual facts and details.

Recent studies show that graphics facilitate viewers' performance on complex interpretation tasks through appropriate graphical design. Specifically, research on graphs (Shah *et al.*, 1999; Shah and Carpenter, 1995) suggests they effectively communicate information about patterns and relationships in the data when they enable readers to perceive this information without engaging in complex cognitive processes. Shah *et al.* (1999; Shah and Carpenter, 1995) collected eye-fixation data and verbal protocols to gain an insight into viewers' thought processes when they interpreted line and bar graphs. Shah and Carpenter (1995) found that when line graphs represented relationships about three variables (y as a function of x and z), viewers extracted information about the x–y function but were less likely to interpret information about the z–y functional relations. The researchers concluded that this happens because z–y relations are less explicit and require the users to make more inferences and mental transformations of the data, for example, to calculate differences between data points and then compare these differences.

Shah *et al.* (1999) suggested that displays are computationally efficient when they can shift some of the cognitive demands of their interpretation to the visual perception operations that are carried out more automatically, thus reducing cognitive load. This is likely when graphs are designed based on Gestalt principles of organization, such as connectedness and spatial proximity, and when they present important information in visual chunks. When graphs represent data in visual chunks, viewers can identify patterns and relations in the data by relying on pattern perception processes instead of engaging in complex data transformations. In line graphs, a line connecting data points is perceived as one chunk. This allows line graphs to communicate effectively information about the x–y function that is represented with a line, but not about the z–y relation. In bar graphs, visual chunks consist of bars that are placed close together. Hence, bar graphs facilitate comparisons among categories of data that are presented in close-together bars. These conclusions are consistent with those of Zacks and Tversky (1999) who found that when viewers interpreted bar graphs they tended to make discrete comparisons between individual data points (represented by different bars that were placed in relative distance from each other) whereas when they viewed line graphs they tended to extract information about trends in variable changes. This is because in the bar graphs used in their study, individual values were presented separately in different bars and were therefore perceived as separate units, whereas in line graphs values were connected in lines and were perceived as one unit (chunk) of information. An example of how the Gestalt principles of connectedness and proximity can be applied to the design of bar and line graphs is provided in Fig. 1. The graphs present hypothetical data about changes in the population of three animal species. According to the above principles, Graph A is effective for encouraging viewers to make among-species comparisons for each year, whereas Graphs B and C encourage viewers to make across-year comparisons for each species.

Learner Characteristics. It appears that graphic comprehension and information search is influenced by readers' knowledge and skills. In the study discussed previously, O'Donnell (1993) found that students with high prior knowledge were more successful in finding information in knowledge maps than were low-knowledge students. The former performed better both on questions that required them to search knowledge maps for simple tasks and on questions that required them to draw inferences and integrate facts.

Discussion

The studies reviewed in the previous sections provided support for the visual argument hypothesis. Graphics are more effective than text for communicating information and for facilitating concept relation learning. However, their effectiveness depends on the their visuospatial properties. Only some displays communicate a visual argument.

A general conclusion drawn from this research is that graphical displays can be computationally efficient when they are designed in ways that can make the information they represent salient to learners. Graphics are effective when their interpretation relies more on cognitive processes carried out automatically by our visual perception system and less on complex computational processes. This is accomplished when the design of graphics uses Gestalt principles of organization that take advantage of how viewers tend to perceive and configure visual patterns. For example, clustering individual graph elements in visual chunks, according to the principle of spatial proximity, enables readers to perceive these elements as interrelated group members. When this principle is applied to the design of graphic organizers, intended to communicate information about concept relations, it suggests that graphic organizers be spatially configured in visual clusters that guide readers to perceive these relations (Robinson and Kiewra, 1995). Similarly,

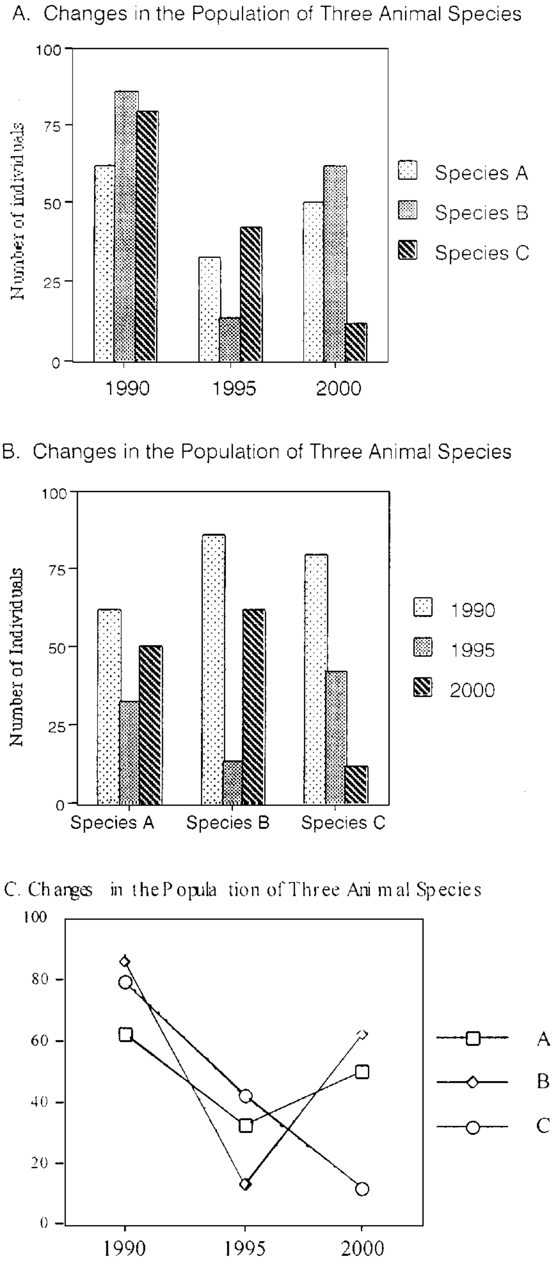

Fig. 1. Bar and line graphs representing hypothetical data about changes in the population of three animal species.

in line and bar graphs the most relevant data points and trends should be presented in visual chunks, that is, in lines connecting data points and in bars that are spatially close together (Shah *et al.*, 1999).

One of the issues that this research program has not adequately addressed is the role of learner's prior knowledge. Studies that have examined the role of expertise in the interpretation of graphical representations have shown that the amount and quality of information that people can extract from displays is a function of their subject-matter knowledge. When viewers with limited or no prior knowledge interpret graphics, they tend to extract information at a superficial level. Experts on the other hand tend to look for the underlying scientific principles and phenomena that are represented in the displays and try to understand general patterns and trends in the data (Lowe, 1994, 1996). Therefore, it is likely that being successful at *global* search tasks (Guthrie *et al.*, 1993), that require detecting patterns and finding relationships among categories of information, is also a function of prior knowledge. In other words, graphical displays may be computationally efficient for those learners who have the prior knowledge to use them meaningfully.

THE CONJOINT RETENTION HYPOTHESIS

What is the Conjoint Retention Hypothesis?

The conjoint retention hypothesis was introduced by Kulhavy *et al.* (Kulhavy *et al.*, 1993a, 1994) to explain how geographic maps facilitate information acquisition from a subsequently studied text. Conjoint retention is not a different theory, but an interpretation of dual coding theory applied to map learning, and is compatible with both dual coding and the visual argument hypothesis. It rests on two assumptions. The first one is based on dual coding theory (Paivio, 1990) and claims that there are two separate but interconnected memory codes for representing verbal and visual information. As discussed earlier, based on this assumption, maps can improve students' recall of verbal information because map representations can activate verbal representations during retrieval.

The second assumption—the computational assumption—emphasizes the representational properties of maps (Kulhavy *et al.*, 1993a) and is based on the work of Larkin and Simon (1987). Maps are more advantageous than text because, when they are encoded as intact units, they preserve their visuospatial properties. That is, they contain both information about individual features (such as size, shape, and color of discrete objects) and "structural" information about the spatial relations among these features (such as distance and boundary relations). When maps are encoded as holistic units, learners can generate and maintain mental images of maps without exceeding their working memory capacity because the map features and their structural relations are simultaneously available (Larkin and Simon, 1987). However, if maps provide limited structural information (Kulhavy *et al.*, 1993c) or if students do not recall most of the structural information, then maps lose their advantage because they cannot be retrieved and maintained in working memory as holistic units (Kulhavy *et al.*, 1993b).

Evidence for the Conjoint Retention Hypothesis

Both assumptions of the conjoint retention hypothesis have been investigated with a series of experiments (see Table V for a summary of related studies). As Table V shows, conjoint retention studies typically used reference and thematic maps, and iconic diagrams. Reference maps depict geographic regions and their characteristics. Thematic or statistical maps show the geographic distribution of data and represent variable values or categories (such as amount of rainfall or population growth rate) using color or shading variations. In a typical study, students were asked to study a map, then either hear or read information about map facts (e.g., a narrative describing events regarding a particular region), and later reconstruct the map. Learning was commonly evaluated with "free" or "cued recall" tests. The first required students to recall everything they could remember and the second assessed memory of specific facts or map features. Map reconstruction tasks evaluated how much information about map features and structural characteristics students had actually encoded.

Research conducted by Kulhavy and his colleagues showed that students who studied a map and text together were able to recall more information than did students who used nonvisual study aids, such as notes or underlined text (Dickson *et al.*, 1988), passages containing facts about map landmarks (Kulhavy *et al.*, 1993b), or verbal descriptions of the map's spatial properties (Stock *et al.*, 1995).

According to the second assumption of the conjoint retention hypothesis, maps facilitate learning because when they are encoded as holistic units people's memory representations contain structural information. Some support for this assumption was provided by studies where map organization was disrupted or map information was provided in a nonintegrated fashion (for example, individual features were presented one at a time) and maps were not encoded as intact images. These maps did not aid learning (Kulhavy *et al.*, 1992, 1993c). In addition, another study showed that text recall was related to how accurately students remembered (had encoded) both the features and the structure of the map (Kulhavy *et al.*, 1993b). However, maps

Table V. Summary of Conjoint Retention Studies

Study	Displays	Participants	Learning outcomes	Instructional conditions	Findings
Dickson *et al.* (1988)	Geographic reference map	College students	1. Free and cued recall of text information 2. Map reconstruction	Experiment 2: Students were given a map or a summary of the text (notes or underlined text) prior to reading the text	Experiment 2: Students in the map condition recalled more facts and map features than did the other groups. Students were more likely to recall facts they had encoded during reading
Schwartz and Philippe (1991)	Geographic reference map	College students	1. Free recall of map content 2. Map reconstruction	Students studied the content of a map using two different strategies (clustering the map features either by their conceptual or their spatial relations)	Females tended to encode map features semantically and remember more map features. Only "field-independent" learners (who can perceptually disembed individual map features from their context) used semantic-based encoding successfully
Kulhavy *et al.* (1992)	Geographic reference map	College students	Immediate or delayed (after 14 days) free recall of text information using maps	Students studied a map and then heard a narrative covering events in the town depicted on the map. They used distorted or nondistorted maps to recall text information	Changing the location of map features or removing the map structure reduced the events students recalled when maps were used for retrieval
Schwartz and Wilkinson (1992)	Geographic reference map	College students	Free recall of text information	Students listened to a story and viewed a relevant map. The structure of the map was either hierarchically congruent or incongruent with the text content	Students recalled more text facts when the map was structured so that elements relevant to the text content were salient to the viewers
Kulhavy *et al.* (1993c)	Geographic reference map	College students	1. Map reconstruction 2. Free recall of text information	Students studied an intact map or maps that provided only information about individual map features or lacked contextual information	The students who used intact maps constructed more accurate maps and correctly remembered more events and their location than the other groups

Kulhavy *et al.* (1993)	Geographic reference map	College students	1. Map reconstruction 2. Free recall of text information	Students studied a geographic map and used their reconstruction of the map while hearing a related story	Students' recall of text events was related to how accurately they remembered the map features and structure (map encoding)
Seevak *et al.* (1993)	Geographic reference map	High school students	1. Factual recall (free and probed recall, and multiple choice test) 2. Map reconstruction	Students were taught strategies for how to use a reference map as an organizer when reading text. Strategy transfer was tested a week later	Strategy training improved students' recall of text information both for map-related and map-nonrelated information
Rittschof *et al.* (1994)	Geographic thematic map	College students	1. Map reconstruction 2. Free recall of text information 3. Inference questions about relationships implied in the text	Students read text after or before studying a relevant thematic map	Students who saw the map first recalled more facts, made more correct inferences, and produced more accurate map reconstructions than did students who first studied the text. The effect was higher for map-related facts and inferences. Viewing a primer with information on the title and legend of the map didn't affect fact recall
Stock *et al.* (1995)	Geographic reference map	College students	1. Map reconstruction 2. Free recall of text information	Students studied either a map or its spatial description and then heard a narration with map-related facts	Mental representations generated from a map are superior to those generated from spatial descriptions of the map. Studying a map had a positive effect only when the content of the text was related to the map
Robinson *et al.* (1996)	Graphic organizers (matrix, outlines, and concept maps)	College students	1. Comprehension multiple choice test measuring knowledge of concept facts and concept relations	Students learned about sharks by first using a graphic organizer (matrix, outline, and concept map) or text and then listening to a narrated text	Learning with a matrix or a concept map interfered with performance on a spatial memory task indicating that graphic organizers are processed using the visuospatial sketchpad

(*Continued*)

Table V. (*Continued*)

Study	Displays	Participants	Learning outcomes	Instructional conditions	Findings
Verdi *et al.* (1996)	Biology diagrams	Middle school students	1. Cued-recall test 2. Diagram labeling	Students studied a diagram and then read text (or first read the text and then studied the diagram)	Students who studied the diagram first recalled more text facts and correctly labeled more diagram features than did students who first studied the text
Verdi *et al.* (1997)	Geographic reference map and biology diagram	College students and middle school students	1. Text fact recall 2. Map landmarks recall 3. Placement of landmarks on maps	Students studied a diagram or a map and then read text (or first read the text and then studied the map and diagram)	Both groups of students performed better on all tests when they first studied the visual displays and then read the text
Rittschof and Kulhavy (1998)	Geographic maps (cartogram, data-map, choropleth, and proportional map)	College students	1. Recall of map data 2. Recall of text information	Students read a passage after viewing either one of the four map types or a data table; then, they were tested on memory for map data and text information	Data maps were more effective in conveying map data than the other map types. All map types were moderately effective in facilitating memory of text information
Schwartz *et al.* (1998)	Geographic reference map	College students	1. Text fact recall 2. Map reconstruction	Students listened to passages with or without studying geographic maps. The maps had either familiar or unfamiliar content	Students who used the familiar map remembered more facts than those using the unfamiliar map. The presence of a map enhanced the performance of students in both conditions. Maps were more beneficial when students had some prior knowledge

Robinson *et al.* (1999)	Networks charts/graphic organizers, and concept maps	College students	1. Knowledge of concept facts 2. Knowledge of concept relations	Students studied a text, an outline, a graphic organizer, or a concept map and then were shown either a verbal or a spatial display; then, they were tested on their comprehension of the first display (or text)	Comprehending graphic organizers and concept maps interfered with the spatial concurrent task whereas comprehending outlines and texts interfered with a verbal task. This suggests that the former are processed by the visuospatial sketchpad
Griffin and Robinson (2000)	Geographic maps	College students	1. Free recall of passage facts 2. Memory of spatial display	Students studied a map (or icon/name list or title display) while listening to/reading a passage and then viewed a spatial display; then they were tested on their memory for passage information and spatial display	The memory effects of reference maps are not due to their spatial layout but due to the mimeticism of the icons

facilitate text memory only when they are presented before the text (Rittschof *et al.*, 1994; Verdi *et al.*, 1996, 1997). According to the conjoint retention hypothesis, this occurs because when maps are studied first, they are later activated in working memory while studying the text. Although maps can be maintained without exceeding the limits of working memory, maintaining text while studying the maps is more demanding because text can be processed only serially. In a study conducted by Griffin and Robinson (2000), where text was presented concurrently with maps, maps did not facilitate learning.

Support for the assumption that displays can improve learning because they are encoded spatially was provided by Robinson *et al.* (1996, 1999; Robinson and Molina, 2002) when they used text-based displays, but not reference maps (Griffin and Robinson, 2000). The researchers employed a dual-task methodology, which assumes that information processing can interfere with auditory and visual memory tasks because these tasks involve separate working memory systems. In their studies, college students studied a passage, an outline, a matrix, or a concept map and then performed a verbal or spatial task. The researchers found that visuospatial tasks interfered with learning from matrices and concept maps whereas learning from text and outline was negatively affected by verbal tasks. The results indicated that concept maps and matrices are processed spatially whereas text and outlines are processed verbally. However, in another study, that employed the same methodology but used reference maps, Griffin and Robinson (2000) did not find evidence for spatial encoding of reference maps. The results showed that studying a list of map icons was more effective for learning text information than studying the maps themselves. This suggested that maps might aid learning not because of spatial encoding of their layout but because of visual encoding of their individual elements.

A small number of conjoint retention studies examined the role of learner characteristics and map characteristics relative to what students remember by studying texts and maps. Their findings and implications are discussed next.

Display Characteristics

As mentioned above, maps must be presented as intact units and provide accurate information about the spatial relationships described in the text or the narration in order to be effective (Kulhavy *et al.*, 1993c). In addition, research shows that maps are effective when they present information in ways that minimize their processing (Rittschof and Kulhavy, 1998), a finding consistent with the visual argument hypothesis. One way this can be done is by making text-relevant features more prominent on the map (e.g., using color), than information of little importance (Schwartz and Wilkinson, 1992).

Learner Characteristics

Consistent with other research findings, the small number of studies generated by conjoint retention theory showed that the effectiveness of reference visual materials is affected by the characteristics of the learners who use them. One such critical factor is learners' prior knowledge. For example, Schwartz *et al.* (1998) found that although the presence of maps enhanced learning from text, maps were more beneficial when their content was familiar to the students. In addition, students tended to extract and remember more information about text facts and map features related to their background knowledge.

Another critical factor in learning from reference materials is the strategies that students use to extract information. Students need a repertoire of strategies and to know which to use according to the learning task and the information they need from a display. Scevak *et al.* (1993) found that students can be taught or guided to use appropriate strategies and that text learning improves significantly after strategy instruction. Such strategies include summarizing and relating important text information, placing this information on maps, and using mental imagery to recall text information. In their study, students who used these strategies recalled more text information and were able to maintain these strategies two weeks after strategy learning. Instructors can guide students' learning by cueing strategy use. For example, they can direct students to encode map features either semantically (to cluster features according to their content) or spatially (to cluster features according to their spatial relations), depending on whether students want to learn about individual map features or their spatial relations (Schwartz and Philippe, 1991).

Discussion

Conjoint retention is a hypothesis based on dual coding theory and visual argument that aims to explain how maps facilitate factual learning from text. The contribution of conjoint retention to dual coding theory is the assumption that when maps are encoded as intact images in long-term memory, they retain their structural properties (information about the relative location and relations of their elements). This means that map images are processed and searched more efficiently than are verbal representations when they are retrieved from long-term memory.

Evidence from several studies shows that when students use geographic maps as adjuncts to text, they recall more text information than they would if they studied the text alone. However, it is not clear which of the two theory assumptions—the existence of two memory codes in long-term memory or the structural encoding of displays or both—adequately explain this map effect. As for the first assumption of the theory, there is no direct evidence in conjoint retention studies that maps support text learning because they are encoded as visual representations in long-term memory. One could argue that maps are stored as verbal representations that contain information about their structural properties and later can be reconstructed in working memory from propositions.

As for the second assumption of the conjoint retention hypothesis, research results are rather inconclusive. On one hand, experiments that manipulated the structural properties of maps showed that communicating structural information is crucial for the effectiveness of maps. In addition, research employing a dual-task methodology provided evidence for the spatial encoding of text-based displays. However, in the case of maps, dual-task experiments suggested that the effectiveness of maps does not rely on their spatial encoding but on the visual encoding of their individual icons (Griffin and Robinson, 2000).

Another limitation of the conjoint retention hypothesis is that it can be applied only to specific learning conditions and to some displays. Specifically, the theory aims to explain the value of graphical displays when the goal is the acquisition of factual knowledge. It cannot explain how graphics contribute to thinking in more complex or higher-order tasks, such as conceptual learning and problem solving. Also, according to the theory, maps can impact learning only when they are used before text or narration and when students are given instructions for spatial encoding. This is less likely to happen in authentic learning situations where learners typically study displays concurrently with text (e.g., when they study from textbooks). Finally, it is not clear whether the theory can be applied to graphs and other displays that are not analogical to the referents they represent.

GENERAL DISCUSSION

Toward a Theory of Visual Learning

The three theoretical perspectives presented in this review provide an insight into the cognitive mechanisms involved in learning with graphics. Although they are based on different assumptions, they are not in conflict with one other. The differences between these frameworks arise from their focus on different aspects of graphic processing and their aim to understand the role of graphical displays in different learning situations.

Dual coding explains how graphics and words are processed together and why graphical displays facilitate learning when they are combined with text. According to this theory, the benefits of visual displays are associated with the way our cognitive systems are structured to process and represent visual and verbal information. The visual argument hypothesis is not concerned with the existence of separate cognitive systems for processing and representing words and images. Rather, according to visual argument, the advantage of symbolic visualizations relies on their spatial characteristics. Graphical displays communicate complex content more efficiently than does text because their processing in working memory requires less mental effort. Finally, conjoint retention is based on the other two theories. The theory proposes that maps are mentally represented in a visual format and these representations retain information of the maps' visuospatial properties. Maps can facilitate learning because their mental images have a computational advantage.

In addition, each one of the three theoretical perspectives focuses on different learning situations. Dual coding theory is useful for explaining how knowledge is acquired from text and diagrams. Research guided by the visual argument hypothesis addressed (a) the role of graphic organizers (network charts) in conceptual learning and (b) how graphs and diagrams communicate data trends and relations. Finally, the conjoint retention theory explains how reference maps facilitate acquisition of factual knowledge from text.

Based on the above discussion, dual coding theory and the visual argument hypothesis cannot be considered as competing theoretical perspectives but as research programs that provide complementary findings that can contribute to the development of a single theory of visual learning. The conjoint retention hypothesis provides an example of how ideas and findings that were developed in separate research programs can be combined in frameworks that explain the role of graphics in specific learning situations.

Instructional Implications

The Design of Displays

Publications in the 80s and early 90s, including Larkin and Simon's seminal work (Larkin and Simon, 1987), concluded that only "good" or "computationally efficient" displays are effective for learning. However, at that time it was far from clear how one designs computationally efficient displays. Research findings over the past years now reveal some consistent

Table VI. Summary of Design Principles and Unresolved Questions Related to the Three Theoretical Frameworks

Theoretical framework	Design principles	Unresolved questions
Dual coding	–Graphical displays should address the goal of the task and make target information salient to the viewers –Graphical displays are not effective without explanations that guide learners to observe key details, especially when they are intended for low-knowledge students –Graphical displays should be spatially and timely coordinated with text to minimize cognitive load –Explanations to displays are more effective when provided in auditory narration	–Can both assumptions or only one of them explain why graphics aid learning? –How do the separate cognitive systems work together in complex integration tasks and what is the role of individual differences in such tasks? –What is the number, limitations, and task specialization of the systems? –Is the theory and relative findings applied to graphics other than diagrams? –What makes graphic processing more difficult for low-visuospatial-ability students?
Visual argument	–Effective graphical displays are designed based on Gestalt principles of perceptual organization. This minimizes cognitive processing and allows viewers to perceive relations or data patterns and trends using visual perception mechanisms	–What is the role of learner characteristics (e.g., visuospatial ability, prior knowledge) and how do they interact with graphic characteristics in graphic comprehension? –Can the same design principles be applied to all graphical displays? –How can graphical design support learning for different students?
Conjoint retention	–Maps that are used as adjunct displays for factual learning are more effective when presented before the text (or narration)	–Which of the two assumptions actually explains why maps improve memory of text? –Is the theory applied to graphics other than maps and to tasks other than learning facts from text?

patterns that affect graphic processing. These patterns allow researchers to begin to establish specific design principles. Progress was also made toward understanding which student characteristics affect learning and how these interact with the characteristics of graphics. Table VI summarizes the design principles generated from each research program and the unresolved questions relevant to each group of studies.

A general principle supported by all three theoretical perspectives is that graphical displays are effective when they address the limitations of working memory. This principle applies both to the design of individual graphical displays and to multimedia environments as shown in the points below:

1. Findings from studies with graphs and charts (graphic organizers) show that graphical representations are computationally efficient when they minimize the processing required for their interpretation. Displays are most efficient when their interpretation relies more on visual perception because visual perception is carried out automatically without imposing heavy cognitive load. Recent studies showed that "perceptual effects" (Larkin and Simon, 1987) take place when information in the displays is spatially organized according to Gestalt principles of organization such as connectedness and proximity. For example, when individual pieces of important information are spatially grouped together or connected (e.g., concepts linked or clustered together in a graphic organizer or data values connected to a line in a Cartesian graph), readers are likely to perceive them as being interrelated and to draw perceptual inferences about their relationships instead of engaging in further computations.
2. When provided with materials in multiple sources, such as graphics and text, cognitive processing is demanding because learners must simultaneously attend to all these sources and integrate their information. As a result of limitations in working memory capacity, students may fail to integrate information from the various sources coherently and, therefore, to benefit from the presence of multiple representations. Cognitive processing is facilitated if
    - (a) Presented information is coordinated in time and space, that is, the various sources of information are presented simultaneously and are spatially close (Moreno and Mayer, 1999; Mayer *et al.*, 1996). Processing demands can further decrease if information from different representations is physically integrated into one representation, for example, when verbal information is embedded in the form of labels or notes in graphical displays (Mousavi *et al.*, 1995).
    - (b) Information is presented in different modalities, so that, according to the dual coding model, it is processed by different cognitive systems without overloading working memory (Moreno and Mayer, 1999). For example, verbal information is provided in the form of auditory narration and processed by the verbal system.

   - (c) Graphical displays are not clustered with a lot of information; readers can easily perceive the phenomena or relations that are important.

(3) Finally, when maps are used as reference materials to facilitate learning from text or narration, their effectiveness is maximized when they are provided with or before the text or narration.

Several of the above design principles overlap with suggestions that have already been proposed (e.g., Kosslyn, 1989; Tukey, 1990). For example, 10 years ago Tukey (1990) argued that effective displays have an immediate impact on viewers and enable them to not only read individual numbers but also make quick comparisons and observe phenomena. However, most of these suggestions were based on intuitions of what might make graphics effective and not on findings based on systematic investigations or on a theoretical understanding of graphic processing.

Individual Differences

Students' prior subject-matter knowledge, visuospatial ability, and learning strategies influence the process of learning with graphical representations. For some students, learning with graphical displays may be less efficient and even challenging. Students with low prior knowledge and low visuospatial ability have difficulties extracting information from graphics. Also, when students lack appropriate strategies for using and integrating information from displays, they may fail to take advantage of the displays' computational efficiency. Evidence from a small set of studies suggests that some of these difficulties can be addressed through the design of visualizations that make learning benefits available to a larger number of students. It is also likely that in order to address individual differences, designers and educators may need to represent the same content in different graphic formats. For example, low- and high-knowledge students may benefit from different graphical designs.

Research offers some suggestions on how displays can support learners with low prior knowledge. These students do not always know how to interpret a graphical representation and to integrate information from both graphics and text. Specifically, they may not know what elements in the display are important to attend to and consequently process information at a superficial level. To help these learners, displays need to be accompanied by explanations (e.g., in the form of labels or notes embedded in the displays). These explanations work better when they cue learners to the important graphic elements and details necessary to extract the message(s) that graphics communicate. Also, when displays are used as adjuncts to text, integration of information from both sources can be facilitated if the text provides explicit references to the display thereby guiding students to observe the elements that are important for comprehending each part of the text.

Questions for Future Research

It is sometimes difficult to generalize from the findings of each study or research program. As mentioned earlier, each of the three theoretical perspectives focused on a particular learning situation and a specific type of display. As Table III shows, dual coding studies investigated how we learn and integrate information presented in visual and verbal modalities. The studies reviewed here focused exclusively on diagrams depicting mechanical systems or science processes. Visual argument studies examined the role of various types of charts (knowledge maps, matrices, etc.) in conceptual learning and how graphs, diagrams, and charts aid in the search and interpretation of information (see Table IV). Finally, conjoint retention studies focused mainly on thematic and geographic maps (see Table V). The question that arises is to what extent findings with one set of displays can be generalized to other displays, or whether each theory can be applied to one type of display and symbol system. For example, can dual coding or conjoint retention theory explain learning from text with displays other than iconic diagrams or maps whose elements do not represent concrete objects (e.g., graphs)?

Although significant progress has been made in investigating how to design effective graphics, our understanding of this issue is still under development. On one hand, findings from various studies fall into consistent patterns that can form the basis of design principles. On the other hand, some of these principles are still too general and lack practical value because they cannot be easily instantiated into the design of displays. Part of the problem is attributed to the difficulty associated with transferring principles generated from research with one type of graphics (such as graphs and charts) to the design of other displays such as maps. Another problem is that application of these principles must consider the nature of the task and the information that the displays highlight. As previous research has shown, the effectiveness of certain graphic characteristics and types of graphics depend on the cognitive task for which the graphics are used (Lewandowsky and Behrens, 1999). Thus, if the goal of a graphic organizer is to highlight hierarchical relations, then a hierarchical spatial organizer might be more appropriate than a matrix organizer. Future research should investigate design principles using a larger variety of graphical representations and tasks to better understand the interaction among tasks, graphic characteristics, and types of graphical displays.

Another issue that requires attention is the role of individual differences in learning from graphical displays. First of all, our understanding of the role of prior knowledge, visuospatial ability, and strategies is limited and fragmented because relevant findings come from studies that involved different tasks. Tasks vary in the knowledge they require from learners. It is likely that the general finding that prior knowledge is essential for knowing what information to extract from displays applies only to specific tasks and displays. Also, different tasks require different strategies. Investigating the way individual differences interact with display characteristics in a variety of learning situations can provide a deeper understanding of the repertoire of strategies students need to acquire and to implement for different tasks. In addition, although existing research suggests that visuospatial ability is critical in how students process graphical information, its role in learning from visual displays has not received enough attention. More needs to be known about the sources of difficulty for low-visuospatial students and how they interfere with learning from graphical displays. In addition, researchers should explore how these difficulties can be addressed through the design of displays.

Second, some of the design principles outlined above were generated from studies that involved only a specific category of learners (e.g., students with low subject matter knowledge) or did not control for learner characteristics (most of the visual argument and conjoint attention studies). Although some of the principles are probably effective with all learners, others target only a certain group. For example, it is likely that text that provides explicit cues for processing explanatory diagrams is effective for low-knowledge and less-strategic students but interferes with the performance of knowledgeable and strategic learners. Future research should investigate how the various design principles work with different types of learners.

The last comments concern the general scope of current research. As Tables III–V show, the role of the graphical displays in research was to facilitate information acquisition from text, whether the goal was to gain factual knowledge about geographic locations and relevant events (conjoint retention studies), develop mental models of science processes and mechanical systems (dual coding studies), or learn about concepts and their relations (visual argument). In several of the studies, an effort was made to use tasks that simulated authentic learning situations. For example, often the text or graphical representations or both were borrowed from existing encyclopedias, textbooks, or manuals, and students were engaged in tasks that paralleled classroom activities. However, most of the tasks and materials represent traditional forms of learning. This limits the applications of existing theoretical frameworks to contexts where students acquire knowledge through textbooks and lectures.

On the other hand, current constructivist learning approaches require that students learn not only through textbooks and lectures but also through first-hand experiences and inquiry-based activities (National Research

Council, 1996). The latter contexts allow students to manipulate materials, make observations, collect and analyze data, synthesize information from multiple sources, and draw their own conclusions about what they study. Education reformers (Pea, 1994) argue that the role of graphical representations in constructivist learning is not only to transmit information but to enable students conduct their own investigations. For example, in science learning, microcomputer-based laboratories (computers interfaced with probes) allow students to view real-time graphs that represent changes in the motion or temperature of objects that they can touch and manipulate. Existing cognitive frameworks can provide limited explanations about: (a) what role these symbolic abstractions play in helping students understand aspects of the science processes observed in real time and (b) how students integrate information from graphics and their observations into coherent mental representations of science phenomena. Addressing these issues is critical for deciding when to introduce graphical representations in students' investigations, how to integrate them into hands-on activities, and how to help students make connections between these abstract forms and their concrete experiences. Therefore, future research must expand its scope using tasks that are relevant to contemporary, constructivist learning approaches.

Finally, as Tables III–V show, the participants in most studies are college students. Future research should investigate the same graphical display issues with younger learners. Studies that have looked at developmental differences (Gerber *et al.*, 1995) show that one of the biggest challenges in interpreting graphics for young students is to understand the conventions and symbols they use. This suggests that learning from graphical displays is a complex process for young students and requires special consideration.

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