PERGAMON

International Journal of
Educational Research 31 (1999) 611–623

International Journal of
Educational
Research

www.elsevier.com/locate/ijedures

Chapter 5

Multimedia aids to problem-solving transfer☆

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Abstract

How can students be helped to understand scientific explanations of cause-and-effect systems, such as how a pump works, how the human respiratory system works, or how lightning storms develop? This chapter reviews some encouraging evidence that multimedia learning environments can promote constructivist learning that enables problem-solving transfer. It begins with a description of a multimedia learning scenario, a cognitive theory of multimedia learning, and a set of design principles that lead to constructivist learning. Then, results from more than 40 studies are reviewed. In combination, these studies explore the conditions under which multimedia environments promote problem-solving transfer of scientific and mathematical principles. The concluding section addresses the problem of how multimedia instructional messages can be designed to promote problem-solving transfer.

How can students be helped to understand scientific explanations of cause-and-effect systems, such as how a pump works, how the human respiratory system works, or how lightning storms develop? What can be done to help students learn mathematical procedures, such as how to add and subtract signed numbers, in ways that allow them to use what they have learned to solve new problems? For the past ten years a team of researchers at the University of California, Santa Barbara, has been investigating a promising technique for increasing the understandability of instructional messages — supplementing verbal presentations with pictorial ones (Mayer, 1997). Although the search for problem-solving transfer has a long and somewhat disappointing history in psychology and education (Mayer & Wittrock, 1996), our

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☆This article is based on a presentation at the International Congress of Applied Psychology in San Francisco on August 13, 1998. The following people contributed substantively to the research conducted at Santa Barbara: Richard B. Anderson, Joan Gallini, Shannon Harp, Roxana Moreno, and Valerie Sims.

0883-0355/99/$-see front matter
PII: S0883-0355(99)00027-0

goal is to determine the conditions under which these multimedia presentations lead to problem-solving transfer.

This chapter reviews some encouraging evidence that multimedia learning environments can promote constructivist learning that, in turn, enables problem-solving transfer. Multimedia learning environments are those in which instructional material (such as a scientific or mathematical explanation) is presented in multiple forms of representation, including visual (such as animation or illustration) and verbal (such as narration or text). Constructivist learning occurs when learners seek to make sense of the presented material by constructing a coherent mental representation. Problem-solving transfer occurs when a student is able to use what was learned to solve problems that are different from those presented during instruction.

Consider a situation in which a learner sits at a computer terminal and clicks a button for an explanation of how lightning storms develop. The computer presents a 140-second animation depicting the major events in the formation of lightning along with a simultaneous narration describing the same events in words. Fig. 1 presents selected frames from the animation along with the corresponding narration. This is a multimedia learning scenario because the learner receives instructional messages presented in more than one format — namely, as pictures and as words. A more traditional kind of multimedia presentation consists of a page containing both words and illustrations, such as that shown in Fig. 2.

In order to assess the learner's understanding of the explanation, a transfer test is administered in which the learner is asked to solve problems that go beyond simple retention. Table 1 lists some transfer questions that ask the learner to troubleshoot the lightning system, to redesign the lightning system, or to describe how various elements fit into the lightning system. These types of questions tap problem-solving transfer because they address issues that were not explicitly presented during instruction, but which can be resolved if one understands how lightning storms develop. The learner is given 2.5 min to write answers to each of four transfer questions and a transfer score is computed by tallying the total number of acceptable answers that the learner writes. For example, for question 1 acceptable answers include removing positive ions from the ground or adding positive ions to the bottom of the cloud. For question 2 acceptable answers include the cloud is not above the freezing level or the cloud lacks enough moisture. For question 3 acceptable answers include the air must be cooler than the ground or the cloud's top must be cooler than its bottom. Finally, for question 4 acceptable answers include a difference in electrical charge between the cloud's top and bottom or between the cloud's bottom and the earth's surface.

1. A cognitive theory of multimedia learning

What does it mean to understand a multimedia presentation? To address this question, it is useful to draw on several theoretical frameworks. The first is the idea that humans have separate visual and verbal information processing systems (Clark & Paivio, 1991; Paivio, 1986). A second is the idea that the capacities of the visual and auditory working memory systems are highly limited (Baddeley, 1992; Chandler

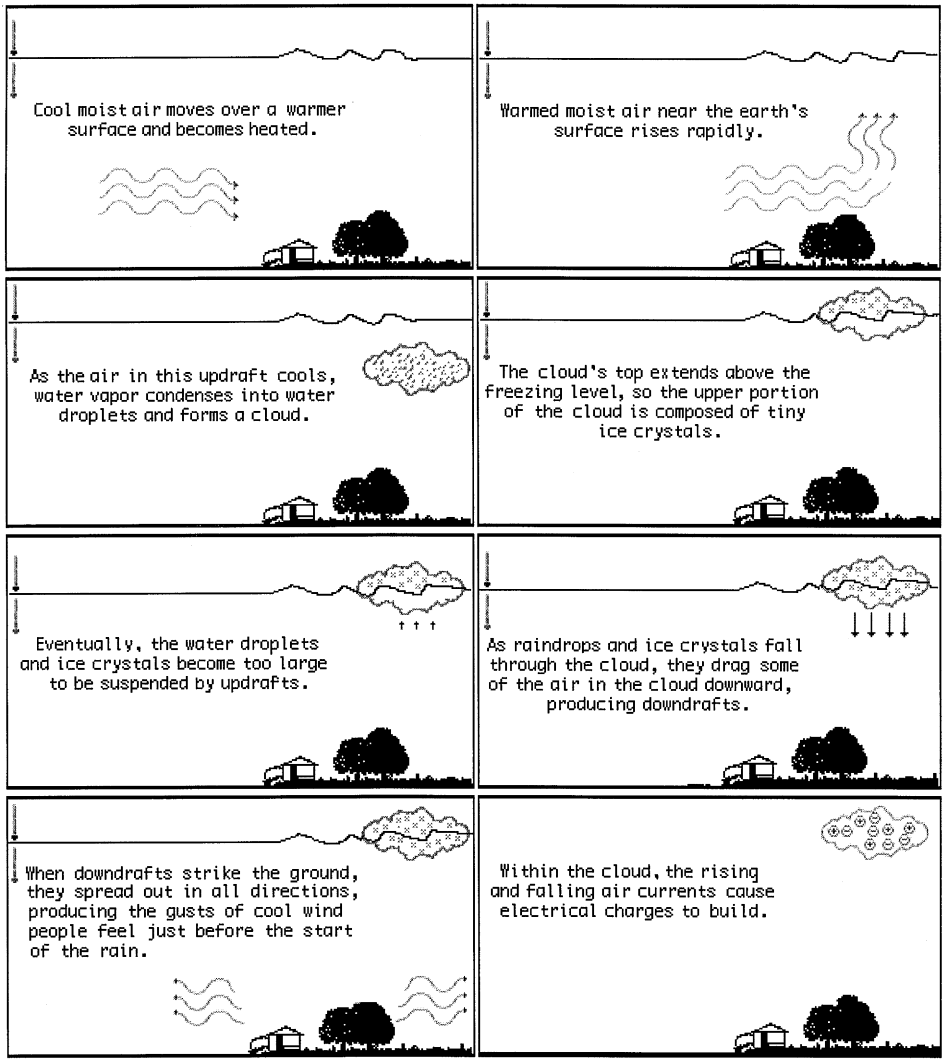

Fig. 1. Selected animation frames and narration about lightning formation.

& Sweller, 1991). A third is the idea that meaningful learning involves active cognitive processing in which learners select relevant information, organize it into a coherent representation, and make connections between visual and verbal representations and prior knowledge (Mayer, 1996; Wittrock, 1989).

Fig. 3 presents a cognitive model of multimedia learning. The idea that humans have separate visual and verbal information processing systems is represented by having a visual system on the top row and a verbal system on the bottom row. The idea that each system has limited capacity is represented by placing parts of each

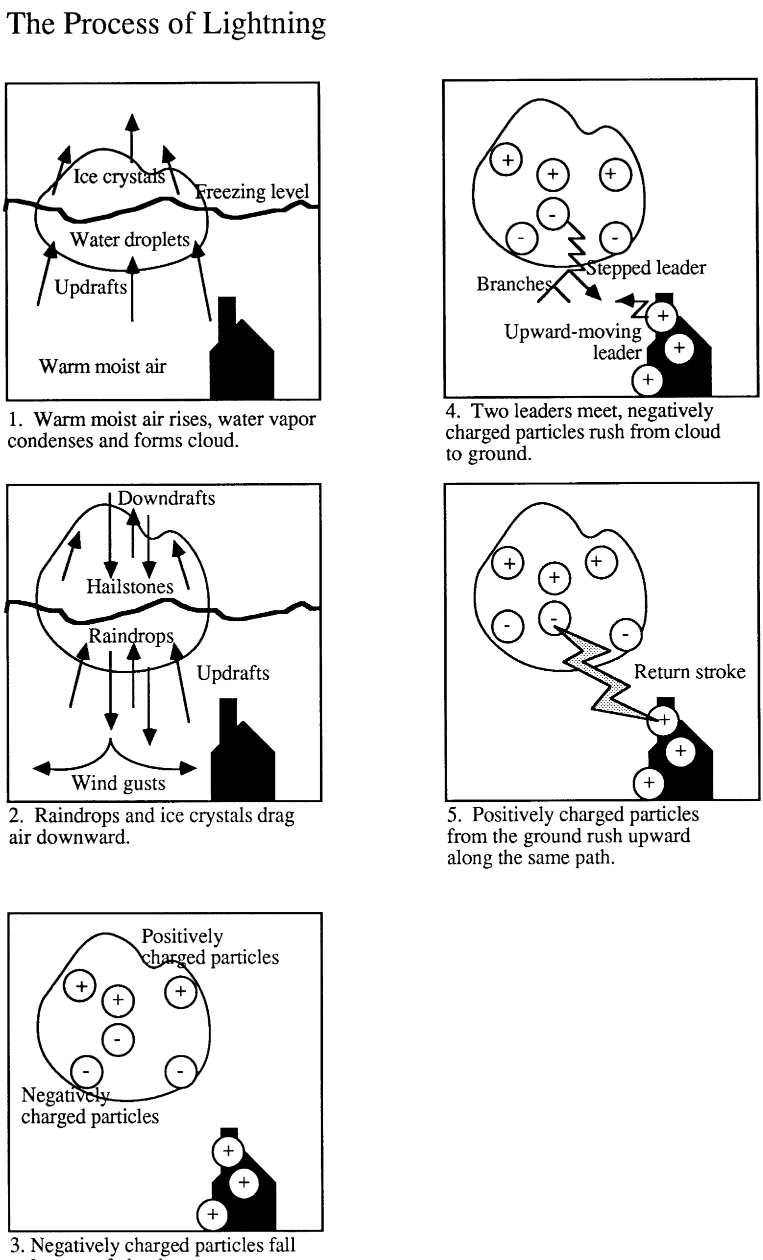

Fig. 2. Text and illustrations about lightning formation.

system under the "working memory" heading. The cognitive process of selecting is represented by the arrow from pictures to images (and from words to sounds); the cognitive process of organizing is represented by the arrow from images to visual

Table 1
Some problem-solving transfer questions about lightning formation

What could you do to decrease the intensity of lightning?
Suppose you see clouds in the sky but no lightning. Why not?
What does air temperature have to do with lightning?
What causes lightning?

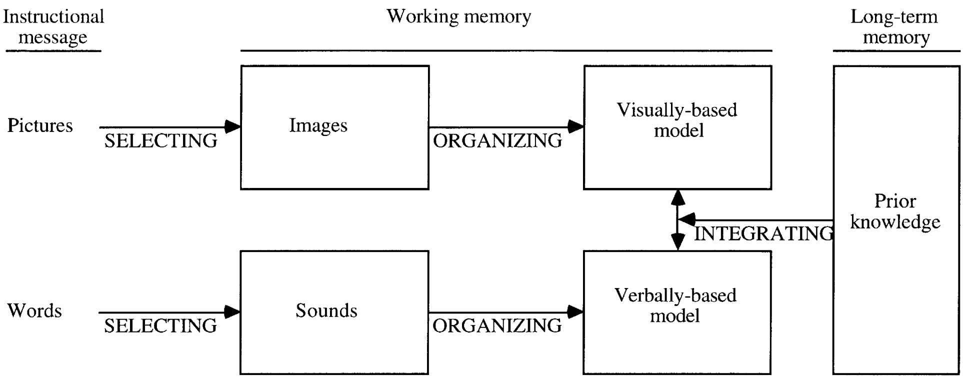

Fig. 3. A cognitive model of multimedia learning.

mental model (and from sounds to verbal mental model); and the cognitive process of integrating is represented as the arrow between visual mental model and verbal mental model (and the arrow from prior knowledge).

When instructional messages are presented in pictorial form the learner selects relevant features to pay attention to, thereby forming a series of mental visual images such as the steps in the lightning process. He or she then organizes the images into a coherent structure such as a visual mental model of the causal chain for lightning formation. When instructional messages are presented in verbal form, the learner selects relevant words to pay attention to, thereby forming a collection of mental word sounds such as the steps in the lightning process. Once again, he or she organizes the words into a coherent structure such as a verbal mental model of the causal chain for lightning formation. The final step is to mentally integrate the visual mental model and the verbal mental model with each other and with existing knowledge.

Constructivist learning occurs when the learner engages in each of these cognitive processes — selecting relevant images and sounds, organizing them into respective visual and verbal mental models, and integrating them with each other and with existing knowledge. Our research is concerned with designing multimedia messages so that they prime these processes. Mayer (1999) has shown how hands-on environments (such as following a laboratory procedure) can lead to rote learning under some circumstances, whereas non-interactive multimedia environments (such as summarized in Figs. 1 and 2) can lead to constructivist learning under some circumstances. Although the multimedia presentations used in this research do not require much hands-on activity from the learner, the goal is to design the presentations in ways that promote constructivist cognitive activity in the learner.

2. The cognitive design of multimedia messages

In the following sections, the conditions under which multimedia presentations are more likely to lead to problem-solving transfer are explored. In particular, I examine the degree to which a series of multimedia design conditions promote constructivist processing for transfer. These conditions are as follows:

- when learners receive words and corresponding pictures rather than words alone (multimedia principle);
- when words and corresponding pictures are presented near rather than far from each other on the page or screen (spatial contiguity principle);
- when words and corresponding pictures are presented at the same time rather than at different times (temporal contiguity principle);
- when words are presented as narration rather than as on-screen text (visual split-attention principle);
- when concurrent non-verbal auditory information is minimized rather than maximized (auditory split-attention principle);
- when alternating visual and verbal information is presented in short rather than long segments (chunking principle);
- when extraneous material is eliminated rather than included (coherence principle); and
- when learners have low rather than high prior knowledge and possess high rather than low spatial ability (individual differences principle).

A collection of studies was carried out in our laboratory in Santa Barbara. In these studies, one way of designing a multimedia message was compared to another (including both computer-based and textbook-based situations). The message provided a scientific or mathematical explanation and the learners were college students unfamiliar with the topic (unless otherwise stated). The learners were assessed on tests of problem-solving transfer and gain scores were computed. To compute these gain scores, the mean number of creative solutions generated by the group receiving the well-designed multimedia presentation was divided by the mean number of creative solutions that the comparison group generated. This ratio was converted into a percent gain score. Although no direct measures of cognitive processing during learning were taken, students' problem-solving transfer performance was used as an indirect measure of constructivist learning. The rationale is that generating creative answers to transfer items is a classic indication of constructivist learning (Mayer & Wittrock, 1996; Mayer, 1999).

2.1. *Multimedia principle: better transfer when learners receive words and corresponding pictures rather than words alone*

A fundamental premise underlying the use of multimedia is that learners understand explanations better when they receive words and corresponding pictures rather than words alone. The rationale for this prediction is that learners are better able to make connections between words and pictures (i.e., engage in the integration process) if words and corresponding pictures are physically presented. When words alone are presented learners may try to form their own mental images and connect those with the words, but this feat may be difficult for most learners.

The multimedia principle was tested in nine studies. Some involved comparisons between animation and narration versus narration alone for computer-based explanations of how bicycle tire pumps work (Mayer & Anderson, 1991, Experiment 2b; Mayer & Anderson, 1992, Experiment 1) and how brakes work (Mayer & Anderson, 1992, Experiment 2). Others involved comparisons of animation and on-screen text versus on-screen text alone for computer-based explanations of a mathematical principle (Moreno & Mayer, in press). Still others involved comparisons between text and illustrations versus text alone for textbook-based explanations of how brakes work (Mayer, 1989, Experiments 1 and 2; Mayer & Gallini, 1990, Experiment 1), how bicycle tire pumps work (Mayer & Gallini, 1990, Experiment 2), or how electrical generators work (Mayer & Gallini, 1990, Experiment 3).

The median gain in problem-solving transfer of the multiple representation group over the single representation group across the nine studies is 87%, as represented on the first line of Table 2. These results provide consistent evidence that adding pictures to words in instructional messages can greatly increase students' ability to use the material in problem-solving transfer.

2.2. *Spatial contiguity principle: better transfer when words and corresponding pictures are presented near rather than far from each other on the page or screen*

The spatial continuity principle is based on the idea that learners are likely to make appropriate connections between verbal and visual representations when words and corresponding pictures are near each other on a page or screen. The rationale is that students need to be able to easily find corresponding visual and verbal information with a minimum of visual search. This prediction was addressed in five studies. Some involved comparisons between animation with nearby on-screen text versus animation with remote on-screen text for computer-based explanations of how lightning storms develop (Mayer & Moreno, 1998a, Experiment 1). Others involved comparisons between illustrations with integrated text versus illustrations with separated text for textbook-based explanations of how lightning storms develop (Mayer, Steinhoff, Bower & Mars, 1995, Experiments 1–3) or how brakes work (Mayer, 1989, Experiment 2). The median gain on problem-solving transfer of the integrated over the separated group across the five studies is 70%, as indicated on the second line of Table 2. These results provide consistent evidence that students are better able to

Table 2
Median percent gain in problem-solving transfer score produced by eight improvements in the design of multimedia learning environments

No. of Expts.	Median gain in transfer (%)	Design principle
9	87	Multimedia principle: Better transfer when learners receive words and corresponding pictures rather than words alone
5	70	Spatial contiguity principle: Better transfer when words and corresponding pictures are near rather than far from each other
7	57	Temporal contiguity principle: Better transfer when words and corresponding pictures are simultaneous rather than successive
4	87	Visual split-attention effect: Better transfer when words are presented as narration rather than as on-screen text
1	90	Auditory split-attention effect: Better transfer when few rather than many non-verbal sounds are presented
1	100	Chunking principle: Better transfer when alternating visual and verbal segments are short rather than long
8	97	Coherence principle: Better transfer when extraneous material is excluded rather than included
4	37	Individual differences principle: (a) Stronger design effects for low- rather than high-knowledge learners
2	64	Individual differences principle: (b) Stronger design effects for high- rather than low-spatial learners

understand multimedia explanations when words and corresponding pictures are near each other on the page or screen.

2.3. Temporal continuity principle: better transfer when words and corresponding pictures are presented at the same time rather than at different times

The temporal continuity principle is based on the idea that learners are more likely to make appropriate connections between verbal and visual representations when words and corresponding pictures are presented simultaneously rather than successively. The rationale for this prediction is that students do not have the working memory capacity to hold an entire animation in working memory until the corresponding narration is presented, or to hold an entire narration in working memory until the corresponding animation is presented. This prediction was addressed in seven studies. The studies involved comparisons between animation presented simultaneously with corresponding narration versus animation followed by or preceded by narration for computer-based explanations of how lightning storms develop (Mayer & Moreno, 1998a, Experiment 4), how bicycle tire pumps work (Mayer & Anderson, 1991, Experiments 1 and 2; Mayer & Anderson, 1992, Experiment 1; Mayer & Sims, 1994, Experiment 1), how brakes work (Mayer & Anderson, 1992, Experiment 2), or how the human respiratory system works (Mayer & Sims, 1994, Experiment 2). The median gain on problem-solving transfer of the simultaneous over the successive group across the seven studies is 57%, as indicated on the third line of Table 2. These results provide consistent evidence that students are better able to understand multimedia explanations when words and corresponding pictures are presented simultaneously rather than successively.

2.4. *Visual split-attention principle: better transfer when words are presented as narration rather than as on-screen text*

The visual split-attention principle is based on the idea that learners are more likely to make appropriate connections between verbal and visual representations when they listen to the verbal explanation (i.e., narration) as they view the visual explanation (i.e., animation). In contrast, when the verbal explanation is presented as on-screen text, visual working memory may become overloaded because both the animation and the text must compete for visual processing capacity. This prediction was addressed in four studies comparing animation presented with concurrent narration versus animation presented with concurrent on-screen text for computer-based explanations of how lightning storms develop (Mayer & Moreno, 1998a, Experiments 1 and 2; Mayer & Moreno, 1998b, Experiment 1) or how brakes work (Mayer & Moreno, 1998b, Experiment 2). The median gain on problem-solving transfer of the narration over the on-screen text group across the four studies is 87%, as indicated on the fourth line of Table 2. These results provide consistent evidence that students are better able to understand multimedia explanations when words are presented as speech rather than on-screen text, and replicate a similar split-attention effect reported by Mousavi, Low and Sweller (1995).

2.5. *Auditory split-attention principle: better transfer when there is little rather than much additional non-verbal auditory information*

The auditory split-attention principle is based on the idea that learners are more likely to make appropriate connections between animations and narrations when there is not much additional auditory information presented, such as environmental sounds and background music. When the narration is presented along with other auditory input such as environmental sounds and music, auditory working memory may become overloaded because both the narration and the other non-verbal sounds must compete for auditory processing resources. This prediction was addressed in a single pilot study comparing animation presented with concurrent narration versus animation presented with concurrent narration, background music, and environmental sounds for computer-based explanations of how lightning storms develop (Mayer & Moreno, 1998a, Experiment 3). The gain on problem-solving transfer of the narration over the narration-plus-other-sounds group is 90%, as indicated on the fifth line of Table 2. These results provide preliminary evidence that students are better able to understand multimedia explanations when the auditory channel is not overloaded with non-verbal sounds such as background music and environmental noises.

2.6. *Chunking principle*: *better transfer when alternating visual and verbal information is presented in short rather than long segments*

The chunking principle is based on the idea that learners are more likely to make appropriate connections between animations and narrations when they can hold corresponding visual and verbal representations in working memory at the same time. Research on the temporal contiguity principle reveals that students have difficulty with this feat when the segments are large — that is, when the entire verbal explanation is presented before or after the entire visual explanation. The explanation for this contiguity effect was that working memory was overloaded by having to hold the large chunks. In contrast, working memory is less likely to be overloaded when corresponding visual and verbal segments are presented in smaller chunks — such as a few words of the narration followed or preceded by a few seconds of the corresponding animation. In this case, learners are more likely to be able to make hold corresponding visual and verbal representations in working memory at the same time. This prediction was addressed in a single pilot study comparing presentation of an entire animation before or after an entire narration (large chunk group) with successive presentations of a short portion of the animation before or after a few words of the corresponding narration (small chunk group) for computer-based explanations of how lightning storms develop (Mayer & Moreno, 1998a, Experiment 4). The gain on problem-solving transfer of the small chunk group over the large chunk group is 100%, as indicated on the sixth line of Table 2. These results provide preliminary evidence that students are better able to understand multimedia explanations when alternating visual and verbal presentations do not overload working memory, and these results complement previous findings concerning the temporal contiguity principle.

2.7. *Coherence principle*: *better transfer when extraneous material is excluded rather than included*

The coherence principle is also based on the idea that learners are more likely to make appropriate connections between animations and narrations when they can hold corresponding visual and verbal representations in working memory at the same time. The foregoing results have demonstrated that the most productive way to present a multimedia explanation is animation with concurrent narration (or illustrations with integrated text). When addition pictures or words are added, learners are less able to make connections between corresponding visual and verbal representations. The extraneous material may overload working memory and may signal readers to focus on inappropriate aspects of the material. This prediction was addressed in eight studies comparing presentation of a concise explanation of how lightning storms develop using relevant illustrations and text versus an embellished explanation containing many extraneous words and/or extraneous illustrations (Mayer, Bove, Bryman, Mars & Tapangco, 1996, Experiments 1–3; Harp & Mayer, 1997, Experiment 1; Harp & Mayer, 1998, Experiments 1–4). The median gain in problem-solving transfer of the concise group over the embellished group across eight studies is 97%, as indicated on the seventh line of Table 2. These results provide consistent evidence that students are better able to understand multimedia explanations when extraneous words and illustrations are excluded.

2.8. *Individual differences principle: stronger design effects on transfer when learners have low rather than high prior knowledge and high rather than low spatial ability*

The individual differences principle is that multimedia effects, contiguity effects, and split-attention effects depend on individual differences in the learner. According to a cognitive theory of multimedia learning, students with high prior knowledge may be able to generate their own mental images while listening to an animation or reading a verbal text so having a contiguous visual presentation is not needed. This prediction was tested in four studies. In these studies, students with high versus low prior knowledge about the specific topic read texts with or without integrated illustrations. The texts explained how lightning storms develop (Mayer et al., 1995, Experiment 2), how brakes work (Mayer & Gallini, 1991, Experiment 1), how pumps work (Mayer & Gallini, 1991, Experiment 2), or how electrical generators work (Mayer & Gallini, 1991, Experiment 3). Prior knowledge was measured by a self-report questionnaire in which students rated their knowledge of the specific subject matter on a 5-point scale (e.g., they rated their knowledge of meteorology before learning about lightning). They also checked applicable items on a list (e.g., they could check items such as "I know the difference between cumulous and nimbus clouds" before learning about lightning). Overall, the effect on problem-solving transfer of adding integrated illustrations to text averaged 5% for the high-prior knowledge learners and 60% for the low-prior knowledge learners, yielding a median difference of 37% as listed in the eighth line of Table 2.

Another prediction based on a cognitive theory of multimedia learning is that students with high spatial ability are better able to hold visual images in visual working memory and thus are more likely to benefit from contiguous presentation of words and pictures. This prediction was tested in two studies in which students with high versus low spatial ability viewed animations with concurrent or successive narration explaining how pumps work (Mayer & Sims, 1994, Experiment 2) or how the human respiratory system works (Mayer & Sims, 1994, Experiment 1). Spatial ability was assessed using short paper-and-pencil tests of paper folding and mental rotation. Overall, the gain in transfer performance for presenting animation and narration simultaneously rather than successively averaged 2% for the low-spatial ability learners and 68% for the high-spatial ability learners, yielding a median difference of 64% as listed in the ninth line of Table 2.

3. Conclusion

In summary, our research has pinpointed some conditions under which multimedia learning can lead to substantial improvements in problem-solving transfer. Overall, students are better able to make sense of a scientific or mathematical explanation when they are able to hold relevant visual and verbal representations in working memory at the same time. When multimedia messages are designed in ways that overload visual or verbal working memory, transfer performance is adversely affected. Thus, this review examines one promising road to transfer; namely, by helping students connect verbal explanations to visual ones.

The results are consistent with a cognitive model of learning in which the learner actively seeks to build connections between visual and verbal representations through the selecting, organizing, and integrating processes summarized in Fig. 3. With respect to the multimedia principle, students are better able to integrate verbal and visual representations when they receive both verbal and visual materials rather than when they receive only verbal material. When only verbal material is presented, the learner may construct an impoverished visual mental model that is insufficient to integrate with the verbal mental model. With respect to the spatial and temporal contiguity, students who receive corresponding visual and verbal material contiguously are more likely to have corresponding visual and verbal mental models in their working memories at the same time than are students who receive visual and verbal materials separately. Thus, contiguous presentations maximizes the chances that the integration process can take place because integration involves making connections between visual and verbal representations held in working memory at a given time. A similar explanation applies to the chunking principle, in that long successive segments reduce the chances that corresponding visual and verbal representations will be in working memory at the same time. With respect to the visual and auditory split-attention effects, adding competing information in a channel can hinder the selecting process resulting in the construction of impoverished mental models. A similar explanation applies to the coherence principle, in that added verbal material can overload the verbal channel.

These conclusions are limited in several ways. First, almost all of the studies involved descriptions of scientific systems, so additional work is needed to examine learning of other kinds of material. Second, almost all of the studies involved college students, so additional work is needed to determine whether the same patterns hold for younger populations. Third, the instructional presentations were short (i.e., less than 5 min) messages presented individually in a laboratory setting, so additional work is needed to examine multimedia learning in school settings. Fourth, constructivist learning was evaluated only indirectly through transfer tests, so additional work is needed to examine learning processes more directly. Fifth, the studies identified several major variables affecting multimedia learning, but additional work is needed to clarify the ways in which these variables might interact.

In conclusion, this review examined the consequences of incorporating visual modes of presentation with the more tradition verbal models of presentation. Although research on multimedia learning is in its early stages, there is encouraging preliminary evidence that well-designed multimedia presentations can help students understand material in ways that lead to problem-solving transfer. The search for principles of multimedia design has potential not only for improving educational practice but also for contributing to cognitive theories of learning.

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