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Aids to computer-based multimedia learning

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Abstract

Computer-based multimedia learning environments — consisting of pictures (such as animation) and words (such as narration) — offer a potentially powerful venue for improving student understanding. How can we use words and pictures to help people understand how scientific systems work, such as how a lightning storm develops, how the human respiratory system operates, or how a bicycle tire pump works? This paper presents a cognitive theory of multimedia learning which draws on dual coding theory, cognitive load theory, and constructivist learning theory. Based on the theory, principles of instructional design for fostering multimedia learning are derived and tested. The multiple representation principle states that it is better to present an explanation in words and pictures than solely in words. The contiguity principle is that it is better to present corresponding words and pictures simultaneously rather than separately when giving a multimedia explanation. The coherence principle is that multimedia explanations are better understood when they include few rather than many extraneous words and sounds. The modality principle is that it is better to present words as auditory narration than as visual on-screen text. The redundancy principle is that it is better to present animation and narration than to present animation, narration, and on-screen text. By beginning with a cognitive theory of how learners process multimedia information, we have been able to conduct focused research that yields some preliminary principles of instructional design for multimedia messages.

Keywords: Multimedia learning; Problem solving; Animation; Narration; Design principles

In order to design multimedia instructional messages that promote understanding in learners, it is useful to be guided by a relevant research-based theory of how people learn (Bransford, Brown, & Cocking, 1999; Lambert & McCombs, 1998).

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Cognitive load theory (Chandler & Sweller, 1991; Sweller, 1999) is an important component in any theory of learning that is intended to guide the design of multimedia learning environments. A major premise in cognitive load theory is that instructional messages should be designed in ways that minimize the chances of overloading the learner's cognitive system. In this article we describe the challenge of designing multimedia learning environments, we outline a cognitive theory of multimedia learning that relies heavily on cognitive load theory, and we summarize some of our empirical research on multimedia learning which supports and clarifies the theory. Based on our research, we propose a series of design principles that are sensitive to cognitive load issues.

1. The challenge of multimedia learning

Computer-based multimedia learning environments — consisting of pictures (such as animation) and words (such as narration) — offer a potentially powerful venue for improving student understanding. However, all multimedia messages are not equally effective, so our focus is on how to design multimedia messages that promote meaningful learning. How can we use words and pictures to help people understand how scientific systems work, such as how a lightning storm develops, how the human respiratory system operates, or how a bicycle tire pump works? This paper presents the latest installment in a multimedia research program that is being carried out at the University of California, Santa Barbara (Mayer, 1997; Mayer, 1999a,b).

We have restricted this research report in three ways: by focusing on explanations, multimedia, and computer-based environments. First, we focus on explanations of how mechanical, biological, or physical systems work. That is, all of our multimedia messages explain the step-by-step operation of a cause-and-effect system in which a change in one part causes a change in another part. Explanation is a basic rhetorical structure and is at the heart of science education. Although other forms of knowledge — such as narrative, description, or enumeration of facts — are also worthy of study, we focus on explanations because they are at the heart of many disciplines and because they are potentially meaningful. Second, we focus on multimedia explanations consisting of words and pictures. Words can be presented as narration or on-screen text; pictures can be presented as animation, video, or static graphics. All of our multimedia presentations depict a causal explanation using animation and describe the same explanation using narration or on-screen text. Words and pictures are the two most common modes of representation and are central to dual-code theories of information processing. Third, we focus on computer-based learning environments in which a learner sits in front of a computer monitor. Computer-based learning is a potentially powerful resource that is not used as much as traditional book-based learning environments.

Fig. 1 presents selected frames from a multimedia presentation on how lightning forms, consisting of a 140 s animation depicting the main steps in lighting formation and corresponding narration describing the main steps in words. To evaluate understanding of the instructional message we ask learners to generate as many answers

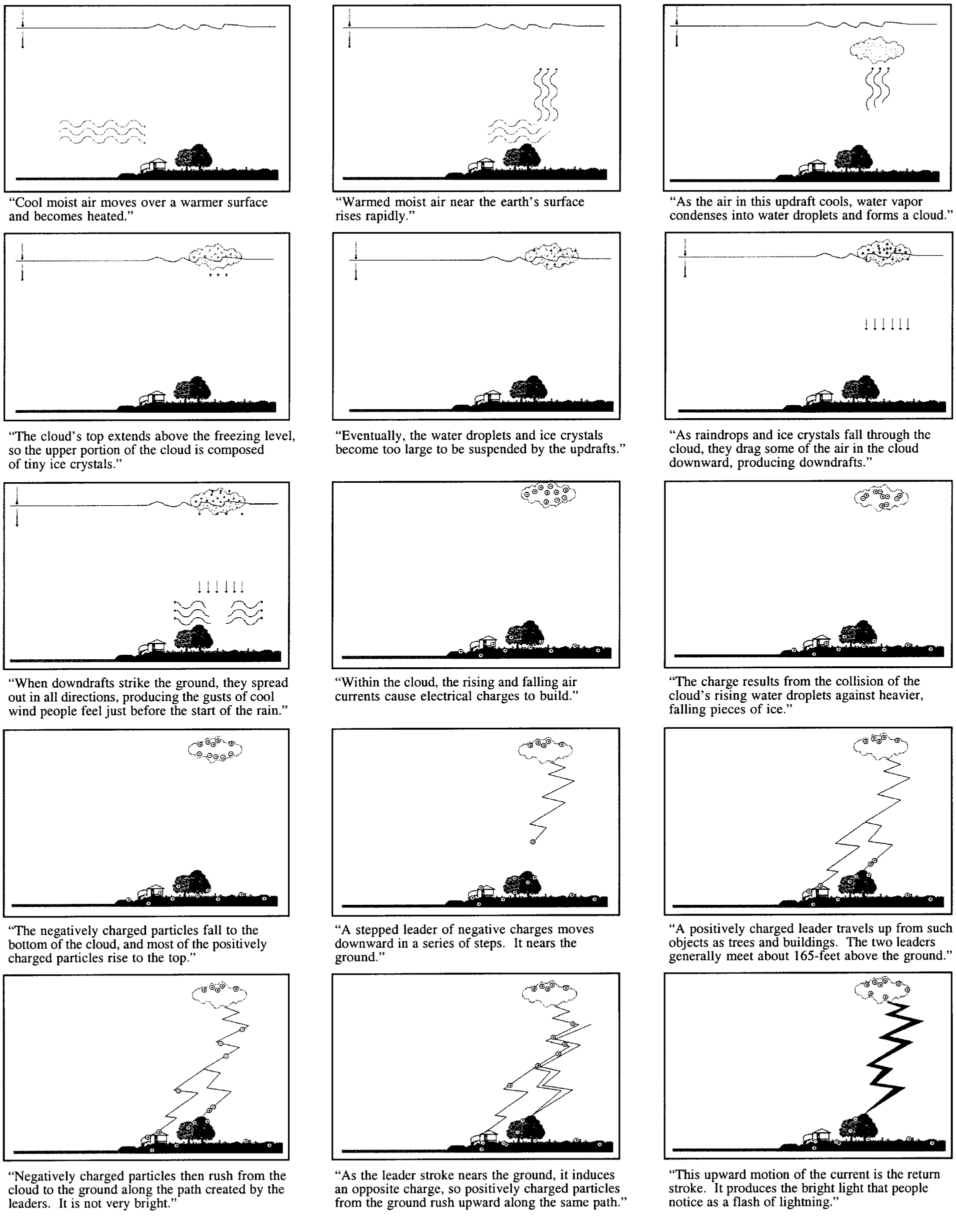

Fig. 1. Selected frames from a multimedia presentation on lightning formation. [Reprinted from Mayer and Moreno (1998) with permission of the American Psychological Association, Copyright 1998.]

as possible to a set of problem-solving transfer problems such as, “What could you do to decrease the intensity of a lightning storm?” or “Suppose you look up and see clouds but no lightning. Why not?” The lightning presentation is an example of a computer-based, multimedia explanation. Other examples include a 45 s animation and narration explaining how a car’s braking system works, a 30 s animation and narration explaining how a bicycle tire pump works, or a 60 s animation explaining how the human respiratory system works. As with the lightning presentation, we evaluated understanding by asking learners to generate as many solutions as possible to a set of problem-solving transfer problems. We focus on problem-solving transfer because we are interested in promoting constructivist learning.

An important challenge of multimedia learning concerns whether it is possible to promote constructivist learning from passive media. Our goal is to promote constructivist learning in which the learner actively engages in cognitive processes for sense making.[1] Yet our multimedia instructional message is passive, in that no behavioral activity nor social activity is required on the part of the learner. The reconciliation of this apparent discrepancy is that constructivist learning depends on the learner’s cognitive activity, not the learner’s behavioral or social activity. Thus, our research is based on the ideas that (a) appropriate cognitive activity can be fostered by passive media (such as well-designed multimedia explanation) and (b) active media (such as highly interactive learning environments) that require hands-on behavioral activity do not necessarily promote appropriate cognitive activity. In short, hands-on activity and social collaboration are not synonymous with constructivist learning, nor are they necessary conditions for constructivist learning to occur. The challenge for designers of multimedia instructional messages is to foster constructivist learning even when no hands-on activity or social activity is possible.

2. A cognitive theory of multimedia learning

We are guided in our research by a cognitive theory of multimedia learning which draws on dual coding theory, cognitive load theory, and constructivist learning theory. From dual coding theory we take the idea that visual and verbal materials are processed in different processing systems (Clark & Paivio, 1991; Paivio, 1986). The visual channel takes input initially from the eyes and ultimately produces pictorial representations; the verbal channel takes input initially from the ears and ultimately produces verbal representations. From cognitive load theory we take the idea that the processing capacities of visual and verbal working memories (or information-

[1] We focus on helping students build meaningful mental repesentations so our approach could be labeled as cognitive constructivism. We do not focus on the social context of learning such as ways in which collaboration can encourage students to build meaningful mental representations. This is an important facet of cognitive constructivism that warrants further study. Furthermore, in this review we do not consider possible individual differences in cognitive processing, although this is also an important issue for further analyses. Finally, we do not subscribe to a radical social constructivist position which disallows mental representations and cognitive processing in individual human minds.

processing channels) are severely limited (Baddeley, 1992; Chandler & Sweller, 1991; Sweller, 1999). In short, presenting too many elements to be processed in visual or verbal working (i.e., too many words or too complex a picture) can lead to overload in which some of the elements are not processed. From constructivist learning theory we take the idea that meaningful learning occurs when learners actively select relevant information, organize it into coherent representations, and integrate it with other knowledge (Mayer, 1996; Mayer, 1999a; Wittrock, 1990). In short, cognitive construction depends on the cognitive processing of the learner during learning. Schnotz and his colleagues have also developed a theory of multimedia learning involving active cognitive processing in multiple channels (Schnotz, Boeckheler, & Grzondziel, 1999; Schnotz, Picard, & Henninger, 1994).

Fig. 2 depicts our cognitive theory of multimedia learning. The top row represents the verbal channel and the bottom row represents the visual channel. The boxes on the left represent the presentation modes for the multimedia instructional message: words are presented as narration and pictures are presented as animation. A cognitively active learner will pay attention to relevant portions of the narration (indicated by the "select words" arrow) and hold these words in verbal working memory (indicated by the "word base" box); similarly, the learner will pay attention to relevant portions of the animation (indicated by the "select images" arrow) and hold these images in visual working memory (indicated by the "image base" box). Next, a cognitively active learner will mentally build connections that organize the words (indicated by the "organize words" arrow) into a cause-and-effect chain (indicated by the "verbal mental model" box); similarly, the learner will mentally build connections that organize the images (indicated by the "organize images" arrow) into a cause-and-effect chain (indicated by the "visual mental model" box). Finally, a cognitively active learner will build referential connections between the visual and verbal mental models and with prior knowledge (indicated by the "integrate" arrows). It is important to note that these processes are likely to occur iteratively, rather than in lockstep order.

For meaningful learning to occur, the learner must carry out each of these cognitive processes, i.e., selecting relevant words and images, organizing them into coherent verbal and visual representations, and integrating corresponding verbal and visual representations. These cognitive activities — particularly, the building of connections

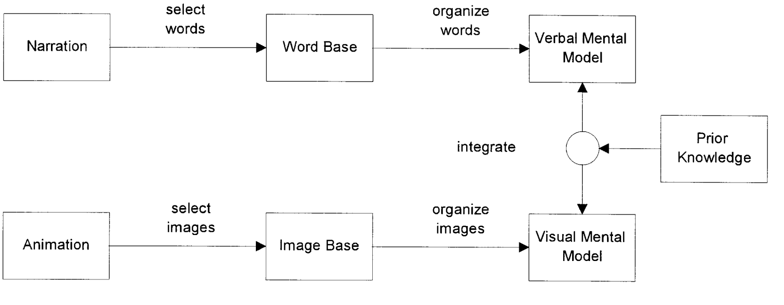

Fig. 2. A cognitive theory of multimedia learning.

between verbal and visual representations — are more likely for situations in which the learner can hold corresponding visual and verbal representations in memory at the same time. Thus, instructional messages should be designed to maximize the chances for such crucial cognitive processing to occur.

By beginning with a cognitive theory of how learners process multimedia information, we have been able to conduct focused research that yields some preliminary principles of instructional design. In this paper we describe five instructional design suggestions that we derived from the cognitive theory of multimedia learning, and show how we and our colleagues tested them.

3. Multimedia aids

The most common mode of instruction is verbal. In explaining how a tire pump works or how a car's braking system works, for example, an instructor is most likely to rely on words — including printed or spoken words. What is the effect of complementing a verbal explanation with a visual one? That is, in explaining how a pump or car's braking system works, does it help to add pictures — including static graphics or animation?

To help answer this question, we compared the learning outcomes of students who listened to a narration describing how pumps or brakes work (narration group) to those who listened to a narration and viewed a corresponding animation (narration and animation group). In particular, we measured student understanding by giving students a problem-solving transfer test and tallying the number of correct answers they generated across a set of four or five problems. In three out of three separate tests, students learned more deeply from narration and animation than from narration alone (Mayer & Anderson, 1991, Experiment 2a; Mayer & Anderson, 1992, Experiments 1 and 2). We computed an effect size by subtracting the mean transfer score for the narration group from the mean transfer score for the narration and animation group and dividing by the standard deviation of the narration and animation group. The first row in Table 1 shows that the median effect size was 1.90, indicating a

Table 1
Five aids to computer-based multimedia learning

Type of aid	Description of aid	Number of tests	Effect size
Multimedia aids	Use narration and animation rather than narration alone	3 of 3	1.90
Contiguity aids	Present corresponding narration and animation simultaneously rather than successively	8 of 8	1.30
Coherence aids	Eliminate unneeded words and sounds	3 of 3	0.90
Modality aids	Present words as narration rather than as on-screen text	4 of 4	1.17
Redundancy aids	Present narration and animation rather than narration, animation, and on-screen text	2 of 2	1.24

strong improvement in understanding when appropriate animation is added to narration.

This result is consistent with the cognitive theory of multimedia learning summarized in Fig. 2. When only words are presented, the learner is likely to build a verbal mental representation but is less likely to build a visual mental representation and mentally connect it with a verbal one. When words and pictures are presented, the learner is more likely to build verbal and visual representations and to make connections between them. If meaningful learning is enhanced when learners can build connections between corresponding visual and verbal representations, then students should learn more deeply when animation is added to narration.

Research on multimedia aids demonstrates that multimedia presentations can result in deeper understanding — as measured by problem-solving transfer — than single medium presentations. In short, it seems to show that multimedia works. However, not all multimedia presentations are equally effective. In the following four sections we explore some of the conditions under which multimedia presentations promote deep understanding. In short, we seek to determine when multimedia works.

4. Contiguity aids

Consider a computer-based multimedia presentation that consists of words (such as a narration) and pictures (such as animation). Furthermore, assume the learner will see the animation only one time and will hear the narration only one time. Is it better to present the animation and narration simultaneously (in which corresponding segments of the animation and narration are presented at the same time) or successively (in which the entire animation is presented before or after the entire narration)?

The rationale for successive presentation is that the learner gets two separate presentations of the same material. According to the information delivery theory, two presentations of the same material spaced in time are better than one. When the explanation is presented simultaneously, the same information is delivered at the same time so the net effect is that the learner receives the information only one time. When the explanation is presented successively, the learner can receive the full explanation twice.

The rationale for simultaneous presentation is based on the cognitive theory of multimedia learning, and its assumption that meaningful learning occurs when students are able to make connections between corresponding visual and verbal representations in working memory. Learners are more likely to be able to hold corresponding visual and verbal representations in working memory at the same time when the animation and narration are coordinated in time. In contrast, with successive presentation, the limitations on working memory capacity make it less likely that corresponding visual representation and verbal representations will be in working memory at the same time.

To test these predictions, we compared students who received animation and narration simultaneously (simultaneous group) with those who received animation before or after animation (successive group). For each comparison, we measured the problem-solving transfer scores of students in each group, because we are most interested in student understanding of the explanation. In eight out of eight separate tests, students learned more deeply from simultaneous than from successive presentation as measured by superior problem-solving transfer scores (Mayer & Anderson, 1991, Experiments 1 and 2a; Mayer & Anderson, 1992, Experiments 1 and 2; Mayer, Moreno, Boire, & Vagge, 1999, Experiments 1 & 2; Mayer & Sims, 1994, Experiments 1 and 2). The median effect size favoring the simultaneous group over successive group was 1.30. Thus, the positive effect of simultaneous presentation across eight studies was consistent and large. These results are consistent with the cognitive theory of multimedia learning and inconsistent with the information delivery theory.

5. Coherence aids

The foregoing results point to the merits of simultaneous presentation, but instructional designers may wish to make the simultaneous presentation more enjoyable. For example, it is possible to embellish a simultaneous presentation by adding some interesting information in the narration or some background music and sounds. In this section, we explore the issue of whether a multimedia explanation should include interesting details or should contain only the core steps in the cause-and-effect chain.

Some students (concise group) received a concise narrated animation in which the basic animation and narration were presented simultaneously. Other students received the same presentation with additional words or sounds (embellished group). The additional words consisted of sentences added to the narration that described interesting facts about lighting, such as a sentence about people in swimming pools being sitting ducks (Mayer, Heiser, & Lonn, 2001, Experiment 1). The additional sounds consisted of the sounds of lightning formation or instrumental background music (Moreno & Mayer, 2001, Experiments 1 and 2).

The rationale for embellishing the presentation is that it makes the material more interesting, thereby motivating the students to work harder to learn. Dewey (1913) was one of the first to argue against this interest theory. More recently, researchers have found that adding interesting but irrelevant sentences to an otherwise boring text does not improve students' memory for the text (Garner, Gillingham, & White, 1989; Harp & Mayer 1997, 1998; Renninger, Hidi, & Krapp, 1992).

In contrast, the rationale for not adding extraneous words and sounds is that students will be less likely to build connections between steps in the causal chain. If extraneous material is presented between various steps in the chain, students may not be able to hold the steps in their working memory at the same time. In short, the extraneous material may fill working memory with material that prevents the learner from building connections among steps in the causal chain.

Does adding extraneous words or sounds affect multimedia learning? In three out of three comparisons, students in the concise group generated more solutions on the problem-solving transfer test than did students in the embellished group. The third row of Table 1 shows that the median effect size was 0.90. Thus, there was consistent and moderately strong evidence that students learn more deeply from multimedia presentations that exclude extraneous words and sounds. These results conflict with the interest theory but are consistent with the cognitive theory of multimedia learning.

6. Modality aids

Multimedia presentations involve presenting pictures and words. In the foregoing studies, the pictures were presented as animation and the words were presented as narration. What would happen if the words were presented as on-screen text — that is as printed rather than spoken text?

According to the information delivery theory, on-screen text and spoken text both serve the same function: they deliver the same information to the learner. Therefore, students should learn equally from printed and spoken text, that is, between narration and on-screen text.

According to the cognitive theory of multimedia learning, the visual and verbal channels are limited in capacity. When words are presented as on-screen text they must be processed — at least initially — through the visual system along with the animation. In this way, the text competes for visual attention with the animation creating what Mousavi, Low, and Sweller (1995) call a split-attention effect. When words are presented as narration they can be processed in the verbal channel, thereby freeing capacity in the visual channel that can be devoted to processing the animation more deeply. In this way, spoken text serves to reduce the load on the visual channel and to increase the chances for deeper cognitive processing.

We tested these predictions by comparing the learning outcomes of students who learned from animation and narration (animation and narration group) with the learning outcomes of those who learned from animation and on-screen text (animation and text group). In four out of four comparisons, the animation and narration group generated more solutions on the problem-solving transfer test than did the animation and text group (Mayer & Moreno, 1998, Experiments 1 and 2; Moreno & Mayer, 1999, Experiments 1 and 2). The fourth row of Table 1 shows that the median effect size was 1.17, indicating a strong and consistent effect. Similar results were obtained by Mousavi et al. (1995). Overall, the results conflict with the information delivery theory and support the cognitive theory of multimedia learning.

7. Redundancy aids

The foregoing results support the use of concise, narrated animations (CNAs) in which concise narration is presented simultaneously with concise animation. Is there any way to improve on this design? One proposal is to present the words both as narration and as on-screen text. In this way, the same event would simultaneously be depicted in an animation segment, in a narration segment, and with on-screen text that is identical to the narration.

The rationale for presenting animation, narration, and on-screen text is that it provides learners with the opportunity to choose the mode of presentation that best suits their learning preference. According to this learning preference theory, some students learn better from animation, others from spoken words, and others from printed words. If we assume that the same information is presented via each mode, then providing more modes allows for more students to be able to use their preferred mode.

The rationale for presenting only animation and narration is that the addition of on-screen text could overload visual working memory. Adding on-screen text can create a split-attention effect in which students must look both at the animation and the text, thereby missing out on some of the presented material. When visual working memory is overloaded, there is less cognitive energy to build connections between visual and verbal representations.

In order to examine these predictions, we compared the learning outcomes of students who learned from animation and narration (animation and narration group) with the learning outcomes of students who learned from animation, narration, and text (animation, narration, and text group). In two out of two comparisons, students in the animation and narration group generated more solutions on the problem-solving transfer test than did students in the animation, narration, and text group (Mayer, Heiser, & Lonn, 2001, Experiments 1 and 2). The fifth row in Table 1 shows that the effect size is 1.24. Adding text to a concise narrated animation did not promote understanding, and in fact, seems to have diminished understanding. Kalyuga, Chandler, and Sweller (1998, 1999) and Kalyuga, Chandler, and Sweller (1999) refer to this pattern as a redundancy effect and have provided evidence in non-computer-based environments. These results conflict with the learning preferences theory and are consistent with the cognitive theory of multimedia learning.

8. Conclusion

8.1. Multimedia instructional messages that minimize cognitive load

Our research results are highly consistent with the basic tenets of cognitive load theory — that working memory can process only a few elements at any one time. Four of our design principles — contiguity, coherence, modality, and redundancy — reflect the theme that students learn more deeply when their visual and/or verbal working memories are not overloaded. In particular, constructivist learning is most likely to occur when learners' needs have corresponding visual and verbal representations in working memory at the same time.

In the contiguity principle, students learn more deeply when they do not have to hold the entire animation in working memory until the narration is presented (or when they do not have to hold the entire narration in working memory until the animation is presented). Compared to simultaneous presentation of animation and narration, successive presentation of animation and narration is more likely to create cognitive overload — a situation that results in reduced levels of understanding as measured by problem-solving transfer.

In the coherence principle, students learn more deeply when they do not have to process extraneous words and sounds in verbal working memory or extra pictures in visual working memory. Compared to concise presentation of animation and/or narration, embellished presentation is more likely to create cognitive overload that results in reduced levels of understanding as measured by problem-solving transfer.

In the modality principle, students learn more deeply when visual working memory is not overloaded by having to process both animation and printed text. When words are presented as printed text, they compete for processing resources with animation in visual working memory, thus resulting in less opportunity to build understanding. When words are presented as spoken text, they do not overload visual working memory, thus allowing for deeper understanding. Finally, the same reasoning applies to the redundancy principle in which presenting both animation and printed text (in redundant presentations) results in overloading visual working memory.

8.2. The design of multimedia instructional messages

Multimedia instructional messages can be influenced by the instructional designer's conception of multimedia learning. When the instructional designer takes an information delivery view, the goal of the multimedia message is to deliver information. When the instructional designer takes a cognitive view, the goal of the multimedia message is to promote knowledge construction in the learner. This is accomplished not only by presenting relevant material in words and pictures, but also by helping the learner to process the presented material in meaningful ways.

All multimedia messages deliver information to the learner, but they are not equally successful in promoting understanding (as measured by problem-solving transfer). We explore five important aids to multimedia learning in this report: multimedia aids, in which students understand more deeply when they receive words and pictures rather than words alone; contiguity aids, in which students understand more deeply when words and pictures are presented simultaneously rather than successively; coherence aids, in which students understand more deeply when unneeded words and sounds are eliminated; modality aids, in which students understand more deeply when words are presented as narration rather than on-screen text; and redundancy aids, in which students understand more deeply when words are present solely as narration rather than as narration and on-screen text.

This report shows how theory-based research in multimedia learning can contribute to an emerging set of design principles and how research in instructional design can contribute to cognitive theory. In this way, the relation between psychology and education is a two-way street in which psychological theories can lead to improvements in educational practice and the challenges of realistic learning environments can help cognitive psychology build better theories. The study of multimedia learning offers a potentially fruitful venue for improving both cognitive theory and educational practice.

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