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Maximizing Constructivist Learning From Multimedia Communications by Minimizing Cognitive Load

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Students viewed an animation depicting either the process of lightning formation or how car brakes work and listened to a corresponding narration describing the steps. The entire animation and narration were presented at the same time (concurrent), the entire narration was presented before or after the entire animation (successive large bites), or short portions of the narration were presented before or after corresponding short portions of the animation for each successive portion of the presentation (successive small bites). Overall, the concurrent and successive small bites groups performed significantly better than the successive large bites groups on remembering the explanation in words (retention), generating solutions to transfer problems (transfer), and selecting verbal labels for elements in a line drawing (matching), but they did not differ significantly from each other. Results are consistent with a dual-process model of working memory in which learners are more likely to construct connections between words and corresponding pictures when they are held in working memory at the same time.

The purpose of this research is to examine theory-based design principles for promoting constructivist learning in multimedia environments. To address this goal, it is necessary to clarify what is meant by multimedia environments, constructivist learning, and theory-based design principles, and to specify predictions concerning ways of designing multimedia environments for constructivist learning.

What Is a Multimedia Environment?

Multimedia environments occur when communications are presented in more than one form, such as when information is presented in a verbal format and in a visual format (Mayer, 1997; Moore, Burton, & Myers, 1996; Reiber, 1990). For example, we constructed a computer-supported multimedia learning environment in which people viewed a short animation depicting the steps in the formation of lightning (or in the operation of a car's brake system) and listened to a short narration describing the same steps. Selected frames from the animation and sample sentences from the narration are presented in Mayer and Moreno (1998) for lightning and in Mayer (1997) for brakes.

What Is Constructivist Learning?

Constructivist learning occurs when learners actively construct meaningful mental representations from presented information. Within the context of our multimedia learning environment, active construction processes include selecting relevant phrases and image sequences concerning lightning formation or braking, organizing them into coherent causal chains of the steps in lightning formation or braking (i.e., building what Mayer, 1999, called *internal connections*), and integrating them with one another and with relevant prior knowledge (i.e., building what Mayer, 1999, called *external connections* or what Paivio, 1986, called *referential connections*). In the case of our multimedia learning example, the meaningful mental representation is a coherent mental model of the causal system of lightning formation (Mayer & Moreno, 1998) or the operation of a car's brake system (Mayer, 1997). People's learning outcomes were evaluated by means of multiple measures of understanding of lightning formation or of how brakes work, including being able to explain the process of lightning or braking (retention test), to generate solutions to new problems (transfer test), and to give the verbal names for elements in the narration (matching test).

What Is a Design Principle?

A design principle is a technique for constructing multimedia environments that foster constructivist learning. Although learners are not physically active in our multimedia environment, it may be possible to promote some degree of cognitive activity that results in constructivist learning. In this study we focus on design techniques for helping people integrate verbal and visual information presented in multimedia environments.

Our research is guided by a cognitive theory of multimedia learning (Mayer, 1997) consisting of three main ideas: (a) dual coding, in which visual and verbal materials are processed in different processing systems (Clark & Paivio, 1991; Paivio, 1986), (b) limited capacity, in which the processing capacities of visual and verbal memory systems are severely limited (Baddeley, 1992; Mousavi, Low, & Sweller, 1995), and (c) generative learning, in which mean-

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ingful learning occurs when learners mentally select relevant information and build coherent connections (Mayer, 1999; Wittrock, 1990).

According to this model, constructivist learning occurs when learners are able to build referential connections between corresponding aspects of the visual and verbal representations of the lightning or braking system. Constructivist learning is fostered when the learner is able to hold a visual representation in visual working memory and a corresponding verbal representation in verbal working memory at the same time. The model implicates working memory load (or cognitive load) as a major impediment to constructivist learning. Although all learners received identical animation and narration in our multimedia environment, we used presentation techniques that varied the cognitive load on working memory. By varying cognitive load, we intended to vary learners' opportunities for building the referential connections needed for constructivist learning.

How Can Multimedia Communications Foster Constructivist Learning?

A straightforward design principle is that learners are better able to construct mental models when corresponding visual and verbal representations are in working memory at the same time. This situation is created when the narration and animation are presented concurrently and is hindered when the narration and animation are presented successively. Consistent with this analysis, previous work using different materials (Mayer, 1997) has produced evidence for a contiguity effect in which students perform better on retention and transfer when they view the animation concurrently with the corresponding narration (concurrent group) than when they view the animation before or after the narration (successive group).

The present study tests the model in more depth by considering the issue of how much visual and verbal information can be held in working memory at one time. Clearly, presenting the full animation and full narration successively (which we call *successive large bites*) can overload working memory such that it is not possible to hold all of the narrative in working memory until the animation is presented (or to hold all of the animation in working memory until the narration is presented). However, consider what would happen if we presented one chunk of animation—depicting only a short sequence—followed by one corresponding chunk of narration—describing only a few events—and so on (*successive small bites*). Similarly, we could present one chunk of animation followed by its corresponding chunk of narration, and so on (successive small bites). If the size of the chunk does not exceed working memory capacity, the learner should be able to make connections between corresponding words and pictures, in the same way as when animation and narration are presented concurrently.

Our hypothesis in this research is that learners are better able to construct mental models of causal systems when corresponding visual and verbal representations are held in working memory at the same time. The rationale for this prediction is that learners are more likely to build referential connections (Clark & Paivio, 1991; Paivio, 1986) between corresponding parts of the visual and verbal representations when these representations are held in their respective visual and verbal working memories (Baddeley, 1992) at the same time. Our predictions are that (a) the concurrent group would outperform the successive large bites group on multiple learning measures, thus replicating the contiguity effect within the new domain of lightning formation or brake operation, and (b) the successive small bites group would perform equivalently to the concurrent group and would outperform the successive large bites group on multiple measures of learning, thus providing an important test of the cognitive theory of multimedia learning.

Experiment 1

Method

Participants and design. The participants were 60 undergraduate college students recruited from the psychology subject pool at the University of California, Santa Barbara. There were 12 students in each of five groups: concurrent, AN, NA, ANAN, and NANA. All participants indicated a low level of experience in meteorology when they completed a participant questionnaire.

Materials. The paper-and-pencil materials consisted of a participant questionnaire, retention test, matching test, and a four-page transfer test, with each typed on 8.5- × 11-in. (21.6- × 27.9-cm) sheets of paper. The participant questionnaire solicited information concerning the participant's age, gender, Scholastic Achievement Test (SAT) scores, and experience with meteorology. The retention test contained the instruction, "Please write down everything you can about the process of lightning" at the top of the page and the instruction, "Please keep working until you are told to stop" at the bottom of the page. The transfer test contained the following four questions at the top of each of four respective sheets of paper: (a) "What could you do to decrease the intensity of a lightning storm?" (b) "Suppose you see clouds in the sky, but no lightning. Why not?" (c) "What does air temperature have to do with lightning?" (d) "What do electrical charges have to do with lightning?" At the bottom of each sheet of the transfer test appeared the instruction, "Please keep working until you are told to stop." The matching test consisted of four frames from the animation along with the following printed instructions:

> Circle the cool moist air and write C next to it. Circle the warmer surface and write W next to it. Circle the updraft and write U next to it. Circle the freezing level and write F next to it. Circle the downdraft and write D next to it. Circle the gusts of cool wind and write G next to it. Circle the stepped leader and write L next to it. Circle the return stroke and write R next to it.

The computerized materials consisted of five multimedia programs written with Director 4.0 (Macromedia, 1994) and adapted from a program used by Mayer & Moreno (1998). The concurrent program presented a 140-s animation depicting the sequence of events in the formation of cloud-to-ground lightning, along with simultaneous narration describing each step in words that were spoken at a slow rate in a male voice. The animation and narration included the following events: cool moist air moving from the ocean to the land, warmed moist air rising, water vapor condensing to form a cloud, the cloud rising above the freezing level, ice crystals forming in the top of the cloud, downdrafts dragging particles downward, downdrafts creating gusts of wind on the earth's surface, updrafts and downdrafts colliding within the cloud, positive and negative charges building in the cloud, negative charges falling to the bottom of the cloud and positive charges moving to the top of the cloud, a negative stepped leader traveling from the cloud toward the ground, a positive stepped leader traveling from the ground to the cloud, the leaders meeting, the negative charges following the path to the ground, the positive charges following the path to the cloud, and the return stroke creating a visible flash. The AN program consisted of the 140-s animation followed by the 140-s sound track; the NA program consisted of the 140-s sound track followed by the 140-s animation. For the ANAN and NANA programs, the animation was broken into 16 segments depicting the steps described above, and the narration was broken into 16 sentences describing the same steps. The ANAN program consisted of an animation segment followed by the corresponding narration segment for each of the 16 segments in order; the NANA program consisted of a narration segment followed by the corresponding animation segment for each of the 16 segments in order. The AN, NA, ANAN, and NANA programs each totaled 280 s, with 140 s devoted to animation alone and 140 s devoted to narration alone.

The apparatus consisted of five Macintosh IIci computer systems, each of which included a 14-in. (35.6-cm) color monitor and Sony headphones.

Procedure. Participants were tested in groups of 1 to 5 per session, with each participant randomly assigned to a treatment group. Each participant was seated in a cubicle so that he or she could not see other participants. First, the participant questionnaire was handed out, and participants were given as much time as they wanted to fill it out and hand it back to the experimenter. Second, the experimenter provided instructions for the multimedia presentation. Participants were told to put on headphones and press any key to start the presentation; further, they were told they would be asked to answer some questions based on the material after the presentation ended. After the multimedia presentation, which lasted 140 to 280 s, participants were given the retention test and told they would have 6 min to write down "everything you can remember about the process of lightning." After 6 min, the retention test was collected, and the first sheet of the transfer test was handed out along with instructions to "keep writing until I tell you to stop." Participants were given 2.5 min to answer the question, after which it was collected and the next transfer sheet was administered in the same way. After all four transfer sheets were completed, the matching test was presented along with instructions to circle and label each of the eight items listed on the sheet. After 5 min, the matching test was collected, and the participant was excused.

Table 1
Experiment 1: Mean Scores and Standard Deviations by Five Groups on Three Tests

	Retention test		Transfer test		Matching test	
Group	*M*	*SD*	*M*	*SD*	*M*	*SD*
N	5.25	1.29	5.58	1.17	7.25	1.06
NANA	4.67	1.97	5.42	1.83	6.83	1.03
ANAN	5.00	1.48	4.92	1.62	6.42	1.68
NA	4.08	1.88	2.50	1.83	4.17	2.08
AN	2.42	1.93	2.67	1.24	5.25	2.09

Note. N = concurrent presentation of animation and narration; NANA = successive small bites of narration followed by animation; ANAN = successive small bites of animation followed by narration; NA = successive large bites of narration followed by animation; AN = successive large bites of animation followed by narration.

Results

Table 1 presents the mean score (and standard deviation) for each of the five groups on each of the three tests. The range of potential scores was 0 to 8 for each test. Analyses of variance (ANOVAs) were conducted on the retention, transfer, and matching scores of the five groups; Tukey tests (with alpha less than .05) revealed that the NA and AN groups did not differ significantly on any of the three tests and that the NANA and ANAN groups did not differ significantly on any of the three tests. Therefore, for purposes of this study, the AN and NA groups were combined into the successive large bites group, and the ANAN and NANA groups were combined into the successive small bites group. Table 2 presents the mean score (and standard deviation) for each of the resulting three groups on each of the three tests. For each dependent measure, we conducted an ANOVA with treatment as the between-subjects variable, followed by Tukey tests (with alpha at .05).

Retention test. The retention test was scored by tallying the number of steps in the causal chain that the participant included in his or her written answer out of a total possible of eight idea units. Given that participants had limited time to write an answer, their retention score provides an indication of the degree to which they selected events in the causal chain as being important. The first two columns of data in Table 2 show the mean number of correctly recalled idea units (and standard deviations) for the concurrent group, the successive small bites group, and the successive large bites group. There was a statistically significant main effect for group, $F(2, 57) = 6.90$, $MSE = 3.19$, $p = .002$, in which the succesive large bites group scored significantly lower than the other two groups, which did not differ significantly from each other.

Transfer test. The transfer test was scored using the same procedure as in Mayer and Moreno (1998) by tallying the number of acceptable answers given on each of the four transfer questions. The transfer test provided a measure of the participant's understanding of the lightning system and required the participant to make inferences based on a mental model of the process of lightning formation. Although there was no limit on how many answers could be generated, the maximum score achieved by any participant was 8. Examples of acceptable answers included removing positive ions from the ground for the question about reducing the intensity of lightning, the cloud's top not being high enough to freeze for the question about lack of lightning, the air being cooler than the ground for the question about the role of temperature, and a separation of positive and negative charges in the cloud for the question about the causes of lightning. The middle two columns of data in Table 2 show the mean number of creative problem solutions (and standard deviations) for the concurrent group, the successive small bites group, and the successive large bites group. There was a significant main effect for group, $F(2, 57) = 22.64$, $MSE = 2.39$, $p = .0001$, in which the large bites group scored significantly lower than the other two groups, which did not differ significantly from each other.

Table 2
Experiment 1: Mean Scores and Standard Deviations by Three Groups on Three Tests

Group	Retention test		Transfer test		Matching test	
	M	*SD*	*M*	*SD*	*M*	*SD*
Concurrent	5.25	1.29	5.58	1.17	7.25	1.06
Successive small bites	4.83	1.71	5.17	1.71	6.63	1.38
Successive large bites	3.25	2.05	2.58	1.53	4.71	2.12

Matching test. The matching test was scored by tallying how many of eight verbal elements the participant was able to label in the graphics. Given that the multimedia presentation contained no labels, the matching represents the extent to which the participant was able to build referential connections between corresponding verbal and visual components of the system. The last two columns of data in Table 2 show the mean number of correct picture–name matches (and standard deviations) for the concurrent group, the successive small bites group, and the successive large bites group. There was a significant main effect for group, $F(2, 57) = 12.23$, $MSE = 2.79$, $p = .0001$, in which the successive large bites group scored significantly lower than the other two groups, which did not differ significantly from each other.

Experiment 2

The purpose of Experiment 2 was to examine whether the results of Experiment 1 could be replicated using different materials.

Method

Participants and design. The participants were 60 undergraduate college students recruited from the psychology subject pool at the University of California, Santa Barbara. There were 12 students in each of five groups: concurrent, AN, NA, ANAN, and NANA. All students indicated a low level of experience in car mechanics in response to a participant questionnaire.

Materials. The paper-and-pencil materials consisted of a participant questionnaire, retention test, matching test, and a four-page transfer test, with each item typed on 8.5- × 11-in. (21.6- × 27.9-cm) sheets of paper. The participant questionnaire solicited information concerning the participant's age, gender, SAT scores, and experience in car mechanics. The retention test contained the following instruction at the top of the sheet: "Please write down an explanation of how a car's braking system works. Pretend that you are writing an encyclopedia entry for people who are not already familiar with brakes." The transfer test contained the following four questions at the top of four respective sheets of paper: (a) "What could be done to make brakes more reliable, that is, to make sure they would not fail?" (b) "What could be done to make brakes more effective, that is, to reduce the distance needed to bring the car to a stop?" (c) "Suppose you press on the brake pedal in your car but the brakes don't work. What could have gone wrong?" (d) "What happens when you pump the brakes (i.e., press the pedal and release the pedal repeatedly)?" The matching test contained a frame from the animation along with the following printed instructions:

> Circle the brake pedal and write B next to it. Circle the piston in the master cylinder and write P next to it. Circle part of the brake line and write L next to it. Circle a smaller piston in a wheel cylinder and write W next to it. Circle part of the brake shoes and write S next to it. Circle part of the brake drum and write D next to it.

The computerized materials consisted of five multimedia programs produced in the same way as in Experiment 1. As described in Mayer (1997), the concurrent program presented a 45-s animation depicting a foot pressing on a brake pedal, a piston moving forward in a master cylinder, brake fluid being compressed in the brake line, pistons moving forward in wheel cylinders, pistons in the wheel cylinders pressing against brake shoes, brake shoes pressing against a spinning brake drum, and the wheel slowing down to a stop. The narration consisted of the following six segments: (a) "When the driver steps on the car's brake pedal," (b) "a piston moves forward inside the master cylinder." (c) "The piston forces brake fluid out of the master cylinder and through the brake lines to the wheel cyclinders." (d) "In the wheel cylinders, the increase in fluid pressure makes a set of smaller pistons move." (e) "The smaller pistons activate the brake shoes." (f) "When the brake shoes press against the drum, both the drum and the wheel slow down or stop." The AN program consisted of the 45-s animation followed by the 45-s sound track; the NA program consisted of the 45-s sound track followed by the 45-s animation. For the ANAN and NANA programs, the narration was broken down into six segments. The ANAN program consisted of an animation followed by a corresponding narration segment for each of the six segments in order; the NANA program consisted of a narration segment followed by corresponding animation for each of the six segments in order. The AN, NA, ANAN, and NANA programs each totaled 90 s with 45 s devoted to animation alone and 45 s devoted to narration alone.

Experiment 2 involved the same apparatus as in Experiment 1.

Procedure. The procedure was identical to that in Experiment 1, except the retention test lasted 5 min and the verbal instructions were to write down "everything you can remember about how car's brakes work."

Results

The tests were scored, the groups were collapsed, and the data were analyzed as in Experiment 1. Table 3 presents the mean score (and standard deviation) for each of the five groups on each of the three tests. The range of potential scores was 0 to 8 for each test. ANOVAs were conducted on the retention, transfer, and matching scores of the five groups; Tukey tests (with alpha less than .05) revealed that the NA and AN groups did not differ significantly on any of the three tests and that the NANA and ANAN groups did not differ significantly on any of the three tests. Therefore, for purposes of this study, the AN and NA groups were combined into the successive large bites group and the

Table 3
Experiment 2: Mean Scores and Standard Deviations by Five Groups on Three Tests

Group	Retention test		Transfer test		Matching test	
	M	*SD*	*M*	*SD*	*M*	*SD*
N	5.33	1.23	6.17	1.59	5.17	0.94
NANA	5.33	1.30	6.33	2.01	3.92	1.56
ANAN	5.25	1.29	5.83	1.90	5.00	0.74
NA	3.08	1.24	3.08	2.06	3.92	0.79
AN	3.67	1.30	4.33	1.67	4.08	1.24

Note. N = concurrent presentation of animation and narration; NANA = successive small bites of narration followed by animation; ANAN = successive small bites of animation followed by narration; NA = successive large bites of narration followed by animation; AN = successive large bites of animation followed by narration.

ANAN and NANA groups were combined into the successive small bites group. Table 4 presents the mean score (and standard deviation) for each of the resulting three groups on each of the three tests. For each dependent measure, we conducted an ANOVA with treatment as the between-subjects variable, followed by Tukey tests (with alpha at .05).

Retention test. The first two columns of data in Table 4 show the mean number of correctly recalled idea units (and standard deviations) for the concurrent group, the successive small bites group, and the successive large bites group. There was a statistically significant main effect for group, $F(2, 59) = 16.77$, $MSE = 1.60$, $p < .001$, in which the successive large bites group scored significantly lower than the other two groups, which did not differ significantly from each other. This pattern of results replicates that of Experiment 1.

Transfer test. Examples of acceptable answers included installing a backup system for the question about redesigning brakes for reliability, reducing the distance between the brake shoe and pad for the question about redesigning brakes for effectiveness, finding a hole in the brake line for the question about troubleshooting a faulty brake system, and reducing heat or wear in one part of the drum for the question about pumping the brakes. The middle two columns of data in Table 4 show the mean number of creative solutions on the transfer test (and standard deviations) for the concurrent group, the successive small bites group, and the successive large bites group. There was a significant main effect for group, $F(2, 59) = 11.83$, $MSE = 3.52$, $p < .001$, in which the successive large bites group scored significantly lower than the other two groups, which did not differ significantly from each other. This pattern of results replicates that of Experiment 1.

Matching test. The last two columns of data in Table 4 show the mean number of correct picture–name matches (and standard deviations) for the concurrent group, the successive small bites group, and the successive large bites group. There was a significant main effect for group, $F(2, 59) = 5.48$, $MSE = 1.29$, $p < .05$, in which the concurrent group scored significantly higher than the other two groups, which did not differ significantly from each other. This pattern of results differs from the results in Experiment 1, in that the greater mean score of the successive small bites group over the successive large bites group failed to reach statistical significance in Experiment 2.

General Discussion

This study advances our understanding of how to help people integrate verbal and visual information presented in multimedia environments. As expected, the contiguity effect (Mayer, 1997) was fully replicated, because the concurrent group significantly outperformed the successive large bites group on each of three dependent measures in both experiments. The important new findings in this study are that the performance of the successive small bites group was statistically indistinguishable from the concurrent group and was significantly better than the successive large bites group on each of the three dependent measures in Experiment 1 and on two of the three measures in Experiment 2. These findings are consistent with the hypothesis that multimedia learning is enhanced when learners are able to hold corresponding visual and verbal representations in working memory at the same time. However, it should be noted that there was low power for anything but large effects in these studies.

Importantly, the positive effects of minimizing working memory load were obtained on dependent measures that go beyond simple retention. Consistent with our conception of constructivist learning outcomes, multimedia environments that minimized working memory load allowed learners to select relevant information, as measured by the retention test; to build referential connections, as measured by the matching test; and to build integrated mental models that allow for transfer, as measured by the transfer test. This study demonstrates the value of collecting multiple measures of understanding.

These results advance cognitive theory by pinpointing an

Table 4
Experiment 2: Mean Scores and Standard Deviations by Three Groups on Three Tests

Group	Retention test		Transfer test		Matching test	
	M	*SD*	*M*	*SD*	*M*	*SD*
Concurrent	5.33	1.23	6.17	1.59	5.17	0.94
Successive small bites	5.29	1.27	6.08	1.93	4.46	1.32
Successive large bites	3.37	1.28	3.71	1.94	4.00	1.02

important condition that supports multimedia learning. In particular, learners are more able to build referential connections between corresponding visual and verbal representations when both are held in working memory simultaneously. This situation is maximized by concurrent presentation and is minimized by successive presentation (as in the large bites condition). An important theoretical advance discovered in this study is that the advantages of concurrent presentation also hold for the successive small bites condition. Apparently, in the successive small bites condition, learners can hold a small amount of visual information in working memory until corresponding verbal information is presented (or a small amount of verbal information in working memory until corresponding visual information is presented). As long as the bite size does not exceed working memory capacity, small bite presentations foster the same opportunities for building referential connections as do concurrent presentations. In summary, the present study shows that it is not necessary that corresponding visual and verbal segments be presented concurrently (i.e., in physical contiguity) but rather that they be held in working memory at the same time (i.e., in cognitive contiguity).

The practical implications of this research are clear. Multimedia presentations are most effective when corresponding visual and verbal representations can be held in working memory at the same time. Multimedia designers should be leery of situations in which large amounts of visual information are presented without corresponding verbal information or when large amounts of verbal information are presented without corresponding visual information.

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