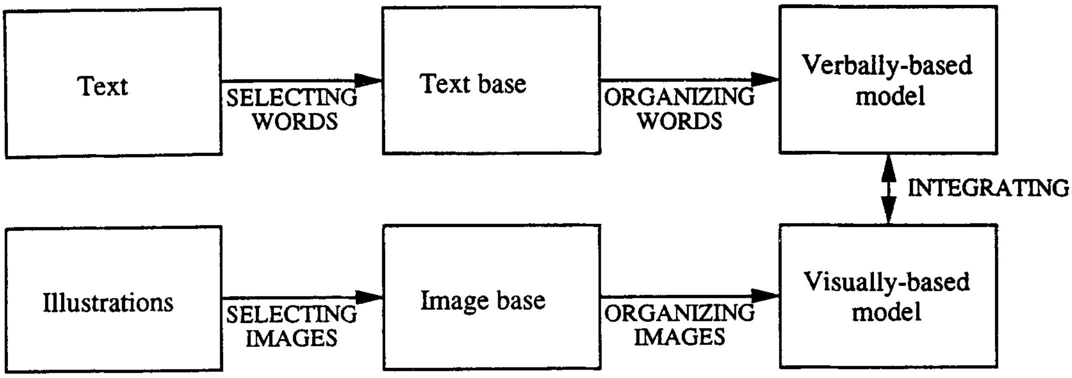
A Generative Theory of Textbook Design: Using Annotated Illustrations to Foster Meaningful Learning of Science Text

□ Richard E. Mayer
Kathryn Steinhoff
Gregory Bower
Rebecca Mars

In three experiments, college students read a text explaining how lightning works and then took problem-solving transfer tests. Some students (integrated group) also viewed illustrations depicting the major stages in the formation of lightning that (a) were placed adjacent to corresponding text paragraphs and (b) contained annotations repeating the verbal cause-and-effect information from the text. Other students (separated group) viewed the same illustrations (a) on a separate page and (b) without annotations, after they had finished reading the text. The integrated group generated approximately 50% more creative solutions on transfer problems than the separated group, and this pattern was stronger for students who lacked experience in meteorology than for high-experience students. The positive effects of integrated illustrations depended on incorporating annotations (i.e., captions and labels) into the illustrations rather than placing illustrations close to corresponding paragraphs. Results were interpreted in light of a generative theory of multimedia learning which posits that meaningful learning requires constructing connections between visual and verbal representations of a system.

□ Although approximately one-third to one-half of the space in science textbooks is devoted to illustrations, most textbook illustrations do not appear to serve an important instructional function (Levin & Mayer, 1993; Mayer, 1993b; Woodward, 1993). For example, following a taxonomy developed by Levin (1989), Mayer (1993b) found that 85% of the illustrations in sixth-grade science textbooks were either decorational—that is, presented a picture that conveyed no useful information such as a drawing of a boy riding a bicycle in a passage on how tire pumps work—or were representational—that is, portrayed a single element such as an unlabeled photo of a rocket ship in a text on flight. In contrast to extensive research on text processing and text design, there has been relatively less research on the potential power of illustrations for fostering learning from textbooks (Houghton & Willows, 1987; Mandl & Levin, 1989; Mayer, 1989a; Schnotz & Kulhavy, in press; Willows & Houghton, 1987). Preliminary research involving scientific text about how pumps, brakes, and electrical generators work has shown that illustrations are most effective in promoting problem-solving transfer when (a) the text explains how a system works, (b) the illustrations contain a series of frames depicting changes in the status of parts of the system, and (c) the illustrations are coordinated with the text (Mayer, 1989b; Mayer & Gallini, 1990). The present study extends this work by examining the role of



annotated illustrations in learning from a textbook passage explaining the cause-and-effect chain of events in how lightning works.

A Generative Theory of Textbook Design

Our work is motivated by the idea that a theory of textbook design should be coordinated with a theory of meaningful learning (Fleming & Levie, 1993; Mayer, 1993b; 1993c). We build such a theory from components of Wittrock's (1974, 1989) generative theory (as well as extensions by Mayer, 1984, 1993c) and Paivio's (Paivio, 1986; Clark & Paivio, 1991) dual coding theory (as well as extensions by Mayer, 1993a, 1993b and by Schnotz, 1993). Although generative theory originally was based on research concerning reader-based aids to text comprehension, such as instruction in the use of appropriate learning strategies, the current study extends generative theory to text-based aids such as annotated illustrations that elicit generative learning strategies in readers. The overarching theme of a generative theory of textbook design is that features of the text design affect the degree to which readers engage in cognitive processes necessary for meaningful learning.

In a generative theory of textbook design, learning is viewed as a constructive process in which learners select and build cognitive connections among pieces of knowledge. Figure 1 summarizes three cognitive conditions for meaningful learning from words and pictures—selecting, organizing, and integrating. The first constructive processes involve attending to visual and verbal information that has entered the cognitive system through the eyes and ears; this process moves information from sensory memory to short-term memory. As indicated in the SELECTING WORDS arrow, the learner must select relevant information from the presented words and build a verbal representation or text base. Similarly, as indicated in the SELECTING IMAGES arrow, the learner must select relevant information from the illustrations and build a visual representation based on the presented visual material, resulting in the construction of what can be called a pictorial representation or image base.

The next step is to organize the selected material in a more coherent way. As indicated by the ORGANIZING WORDS arrow, the learner must reorganize the text base into what can be called a verbal mental model of the situation described in the text. Similarly, as indicated by the ORGANIZING IMAGES arrow, the learner must reorganize the pictorial representation into what can be called a visual mental model of the situation described in the text. Paivio (1986) refers to the selecting and organizing of verbal information as building verbal representational connections and the selecting and organizing of visual information as the building of visual representational connections.

The final step is to build one-to-one correspondences between the visual and verbal representations of the material—a process labeled as INTEGRATING in Figure 1. Paivio (1986) refers to this process as building referential connections. The process is assumed to take place in short-term memory (or a portion of it called working memory), and therefore requires that the visual and verbal representations be held in short-term memory at the same time.

For example, in reading an illustrated text about how lightning works, the *selecting words step* involves verbally representing the text, "negatively charged particles fall to the bottom of the cloud"; and the *selecting images step* involves visually representing a picture showing negative ions at the bottom and positive ions at the top of a cloud. Next, the *organizing words step* involves building a cause-and-effect chain of propositions, which includes the construction of a causal link between the separation of charge within the cloud and the creation of a stepped leader (i.e., "negatively charged particles fall to the bottom of the cloud" is causally related to "negatively charged particles rush from cloud to ground"). Similarly, the *organizing images step* involves building a cause-and-effect chain of images, including building a causal link between an image of negative ions at the bottom and positive ions at the top of a cloud and an image of negative ions from the cloud moving toward positive ions on the surface of the earth. Finally, the *integrating step* involves building connections between corresponding portions of the verbal and visual representations, such as connecting the proposition about negatively charged particles at the bottom of the cloud with the image of negative ions at the bottom of the cloud. Accordingly, meaningful learning consists of building a coherent mental representation of a cause-and-effect system in short-term memory, and can be measured by problem-solving transfer.

We propose that learners are most able to build connections between verbal and visual representations when the corresponding text and picture representations are actively held in memory at the same time—a situation that is more likely to occur when text and illustrations are presented contiguously on the page rather than separately, or when learners have sufficient experience to generate their own mental images as they read the text. We therefore predict that (a) students who receive illustrations integrated with text will produce more solutions for problem-solving questions than students who receive illustrations separated from text, and (b) these effects will be greater for students who have little rather than much experience about meteorology. We conducted three experiments to test these predictions.

EXPERIMENTS 1 AND 2

In Experiment 1, we identified a text design principle that improves problem-solving performance by 50% for inexperienced learners. Given the practical importance of this effect, Experiment 2 was conducted as a replication and extension of Experiment 1. An important new theoretical issue examined in Experiment 2 concerns whether the effect is equally strong for low- and high-experience learners.

Method

Subjects and design. In Experiment 1, 14 low-experience college students served in the integrated group and 14 low-experience college students served in the separated group. An additional 5 subjects indicated that they possessed high experience in meteorology, and therefore were not included in Experiment 1. In Experiment 2, 14 low-experience and 14 high-experience college students served in the integrated group, and 14 low-experience and 14 high-experience college students served in the separated group. The subjects in both experiments were recruited from the Psychology Subject Pool and received credit towards a requirement in an introductory psychology course that they were taking. To be classified as low-experience, subjects had to rate their knowledge of meteorology as "very little" on a five-point scale ranging from "very little" to "very much" and had to check fewer than three items on a list of seven weather-related statements such as "I know what a cold front is." To be classified as high-experience, subjects had to rate their knowledge of meteorology as above "very little" and had to check three or more weather-related statements. The criteria for low- and high-experience were patterned after previous studies (Mayer & Gallini, 1990). In Experiment 1, no subject qualifications were required; in Experiment 2, no qualifications were required for half of the subjects and the rest were required to "know what a cold front is."

Materials. In both experiments, the materials consisted of a subject questionnaire, an integrated booklet, a separated booklet, and four problem-solving transfer sheets, each typed on 8½ × 11" sheets of paper[1].

The subject questionnaire asked students to rate their knowledge of meteorology (or weather) on a five-point scale ranging from "very little" to "very much" and to place a check mark next to each of seven items that applied to them, including the following: "I regularly read the weather maps in a newspaper," "I know what a cold front is," "I can distinguish between cumulus and nimbus clouds," "I know what a low pressure system is," "I can explain what makes the wind blow," "I know what this symbol means" [symbol for cold front], "I know what this symbol means" [symbol for warm front]. The experience instrument was based on a similar instrument used by Mayer and Gallini (1990).

The integrated booklet consisted of two sheets arranged in a folder as facing pages in an open book. The sheets contained a 600-word passage and five illustrations about how lightning works. The text was created by the authors, based on high-school science textbooks and encyclopedia entries, including the *World Book Encyclopedia*'s (1992) entry for lightning. In addition to factual information which constitutes a description of the properties and characteristics of lightning, the text included a presentation of the chain of causes and effects which constitutes an explanation of how a lightning storm develops. The illustrations depicted events in the cause-and-effect chain such as warm moist air rising to form a cloud. Each illustration was placed next to its corresponding paragraph that described the events depicted in the illustration; each illustration contained a short caption that repeated the description of cause-and-effect events from the text (requiring a total of 48 words for all illustrations), and each illustration contained labels that repeated key terms from the text (requiring a total of 30 words for all illustrations). The integrated booklet is reproduced in Appendix A.

The separated booklet consisted of two sheets each in a separate folder: a sheet containing the same 600-word text as in the integrated booklet, and a sheet containing the same five illustrations as in the integrated booklet but without any captions or labels.

Each problem-solving transfer sheet contained one of the following four problems:

1. What could you do to decrease the intensity of a lightning storm?
2. Suppose you see clouds in the sky, but no lightning. Why not?
3. What does air temperature have to do with lightning?
4. What causes lightning?

Procedure. Subjects were randomly assigned to treatment groups and tested individually. First, the subject filled out the subject questionnaire and was classified as low- or high-experience as described above. Second, subjects in the integrated group were given 5 minutes to read the integrated booklet, whereas subjects in the separated group were given 5 minutes to read a sheet containing the same 600-word text and then 1½ minutes to examine a sheet containing the same five illustrations but without any captions or labels. This procedure allowed both groups to have the same amount of time to read the words, and insured that the integrated group did not have a reading-time advantage over the separated group. Finally, following instructions to generate as many answers as possible, subjects were given 2½ minutes for each of the four problem-solving questions, presented in the

1. Each experiment also included a recall sheet that asked the students to write down all they could remember from the lesson. The test was administered before the problem-solving text and had a six-minute time limit. However, we do not report on this aspect of the study because our major focus was on students' problem-solving performance.

order indicated above. The time limits were based on previous research (Mayer, 1989b; Mayer & Gallini, 1990).

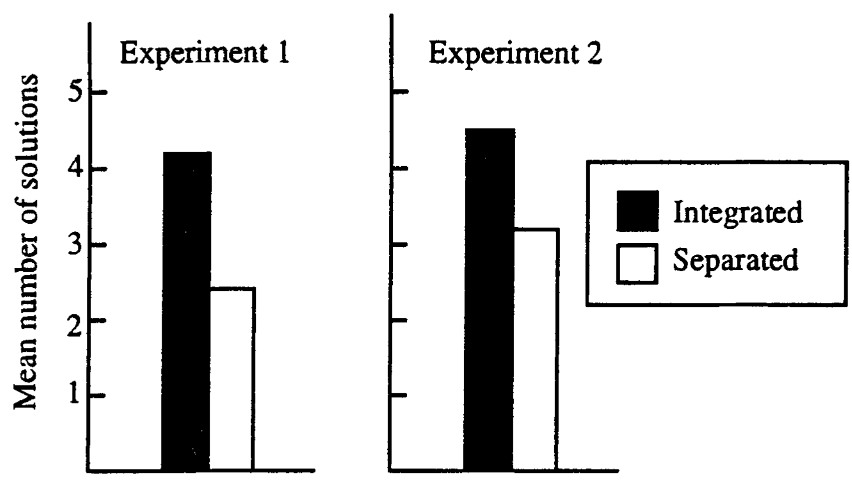
Results

Scoring. On the transfer test, subjects received one point for each acceptable answer on each of the four problem-solving transfer sheets, so the total possible score was unlimited. A list of acceptable answers was established as a scoring key for each of the four transfer questions, although answers did not have to be in verbatim form. For example, an acceptable answer for the first question was to add positively-charged particles to the cloud, or to warm up the cloud so no freezing takes place. For the second question, an acceptable answer was that the cloud was not high enough to be at the freezing level, or that not enough negatively-charged particles were in the cloud. For the third question, an acceptable answer was that there is a difference in temperature between the surface and the air, or that the cloud's top must be at the freezing level. For the fourth question, an acceptable answer was that a difference exists between negative and positive particles, or that there is a temperature difference within the cloud. Subjects' answers were evaluated by two independent scorers who were unaware of the subjects' treatment condition, and disagreements were resolved by consensus.

Prediction 1: Students who receive integrated illustrations generate more creative solutions to problem-solving questions than students who receive separated illustrations.

Our first prediction is based on the idea that integrated illustrations foster readers' building of referential connections more than separated illustrations. The integrated booklet promotes the building of referential connections between words and pictures by presenting the illustration and text contiguously and using labels and captions to pinpoint the relation between text and illustrations. In contrast, the separated booklet interferes with the building of referential connections by presenting illustrations at a different time and place than the corresponding text and by not using any verbal cues within the illustrations to identify how the illustrations relate to the text. Our prediction is based on the idea that a coherent mental representation is needed to generate problem solutions. As shown in Figure 2, the mean numbers of creative solutions correctly

Figure 2 ☐ Mean number of creative problem solutions generated by integrated and separated groups in experiments 1 and 2.



produced on the problem-solving questions for the integrated and separated groups respectively were 4.21 and 2.36 [$t(26) = 2.92$, $p < .01$] in Experiment 1 and 4.64 and 3.50 in Experiment 2 [$t(54) = 2.76$, $p < .05$]. These results are consistent with the idea that contiguous presentation of verbal and visual explanations help students build usable mental models of the explained system.

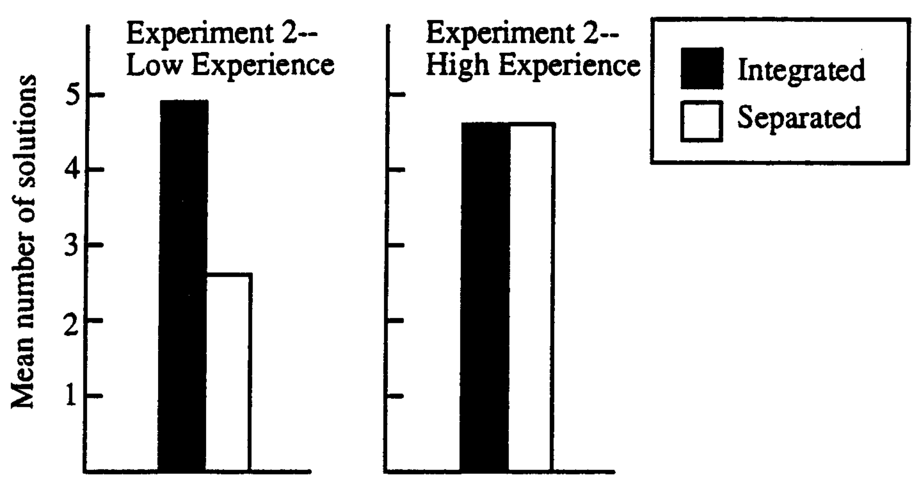
Prediction 2: The advantages of integrated illustrations over separated illustrations on problem-solving transfer is greater for low-experience readers than for high-experience readers.

Our second prediction is based on the idea that learner experience can compensate for uncoordinated instruction (Mayer & Gallini, 1990). When high-experience learners read a text about lightning, they can use their existing knowledge to build useful mental models regardless of whether illustrations are integrated or separated from the text. In contrast, low-experience learners need the support provided by contiguous presentation of words and pictures during instruction. Responses to the subject questionnaire allowed us to designate learners as low- or high-experience in Experiment 2. For low-experience learners in Experiment 2, as shown in the left side of Figure 3, the integrated group generated significantly more creative solutions than the separated group, [means = 4.86 and 2.57 respectively; $t(26) = 4.40$, $p < .01$]. In contrast, for high-experience learners in Experiment 2, as shown in the right side of Figure 3, the integrated and separated groups failed to produce statistically significant differences in problem-solving scores [means = 4.43 and 4.43 respectively; $t(26) = 0$].

EXPERIMENT 3

Experiments 1 and 2 provide consistent evidence that low-experience students are better able to answer problem-solving questions when they read a text with integrated illustrations than when they read a text in which the illustrations are separated from the text. Experiment 2 demonstrates that the effects of integrating text and illustrations are greater for low-experience than high-experience students, so we concentrated on low-experience students in Experiment 3. A problem with Experiments 1 and 2 is that the contrast between separated and integrated illustrations confounds two important variables—*annotation,* that is, whether or not a suc-

Figure 3 □ Mean number of creative problem solutions generated by high- and low-experience students in the integrated and separated groups in Experiment 2.



cinct caption and verbal labels were included with each of the five illustrations, and *placement*, that is, whether or not the illustrations were presented next to the corresponding text paragraph or on a separate sheet of paper. Thus, although we have clearly established in Experiments 1 and 2 that integrated and separated illustrations result in different learning outcomes, it is not possible to unambiguously attribute the effect to annotation, placement, or both. To help untangle this problem, we conducted a third experiment in which students received a booklet containing annotated illustrations placed near the text (*annotated-proximate*), annotated illustrations on a separated page (*annotated-distant*), nonannotated illustrations placed near the text (*nonannotated-proximate*), or nonannotated illustrations on a separate page (*nonannotated-distant*), and then took tests measuring problem-solving transfer. If the positive effects of integrated illustrations are caused by both annotation and placement, then the annotated-proximate group should perform better than the other three groups on transfer measures; if the effect is caused mainly by annotation, then the two groups receiving annotated illustrations should outperform the two groups receiving nonannotated illustrations; finally, if the effect is mainly caused by placement, then the two groups receiving illustrations with the text should outperform the two groups receiving illustrations on a separate page.

Method

Subjects and design. The subjects were college students who lacked experience in meteorology, that is, equivalent to the subjects in Experiment 1 and the low-experience subjects in Experiment 2. Eighteen subjects served in each of four instructional groups: annotated-proximate (AP), annotated-distant (AD), nonannotated-proximate (NP), and nonannotated-distant (ND). The treatments were based on a 2 × 2 factorial design, with the first factor being whether or not the illustrations contained words such as labels for objects in the illustrations and short captions summarizing the actions in each illustration (i.e., annotated versus nonannotated), and the second factor being whether the illustrations were presented on the same page as the text or a different page from the text (i.e., proximate versus distant). The AP group received the passage in Appendix A and corresponds to the integrated groups in Experiments 1 and 2, whereas the ND group corresponds to the separated groups in Experiments 1 and 2.

Materials. The subject questionnaire and four problem-solving transfer questions were identical to those used in Experiments 1 and 2. In addition, there were four instructional booklets: The AP booklet was identical to the integrated booklet used in Experiments 1 and 2; the ND booklet was identical to the separated booklet used in Experiments 1 and 2; the NP booklet was identical to the AP booklet except that the illustrations contained no captions or labels; the AD booklet was identical to the ND booklet except that the illustrations contained the same captions and labels as in the AP booklet.

Procedure. The procedure was identical to that used in Experiments 1 and 2. Subjects in the AP and NP groups had 5 minutes to read their respective two-page instructional booklets; subjects in the AD and ND groups had 5 minutes to read their text sheet which was then removed and 1½ minutes to examine their respective illustration sheets.

Results

Scoring. The experience score was computed as in Experiments 1 and 2. The transfer tests were scored as in Experiments 1 and 2.

Prediction 1: Students who receive integrated illustrations generate more creative solutions to problem-solving questions than students who receive separated illustrations.

In Experiments 1 and 2, low-experience subjects generated more creative solutions when they received integrated rather than separated illustrations. If this pattern is replicated in

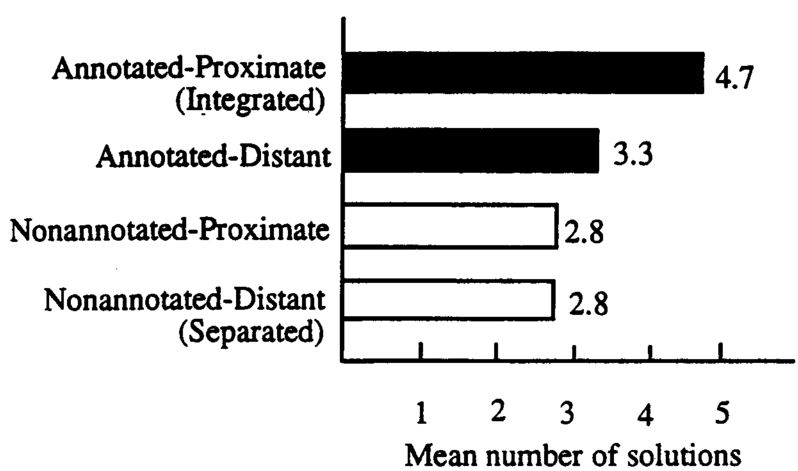
Experiment 3, the AP group would perform better than the ND group on problem-solving transfer. Figure 4 shows the mean number of creative solutions generated by each group in Experiment 3. We conducted a t test on the problem-solving transfer scores of the AP group (which is equivalent to the integrated group in Experiments 1 and 2) and the ND group (which is equivalent to the separated group in Experiments 1 and 2). As predicted, the AP group produced significantly more solutions to problems than the ND group [means = 4.72 and 2.78, respectively, $t(34) = 3.36$, $p < .01$]; this result replicates the difference between integrated and separated groups in Experiments 1 and 2.

Do the advantages of integrated illustrations over separated illustrations on problem-solving transfer depend on whether or not the illustrations are annotated, placed near corresponding text, or both?

Across three experiments, we have found that students generated approximately 50% more creative problem solutions when illustrations were annotated and placed on the same page as corresponding text (integrated group in Experiments 1 and 2; AP group in Experiment 3) than when illustrations were not annotated and were presented on a separate page from the text (separated group in Experiments 1 and 2; AD group in Experiment 3). The major new issue addressed in Experiment 3 concerns the extent to which the advantage of the integrated (or AP) group over the separated (or ND) group can be attributed to (a) whether or not illustrations contain labels and captions (annotated versus nonannotated), (b) whether or not illustrations are placed on the same page as corresponding text (i.e., proximate versus distant), or (c) both.

To help answer this question, we examined the mean number of creative solutions produced in each of the four treatment groups in Experiment 3 (4.72 for AP, 3.33 for AD, 2,82 for NP, and 2.78 for ND) as shown in Figure 4, and conducted a 2 (annotation) × 2 (placement) ANOVA on these problem-solving scores. First, if annotating the illustrations with captions and labels encourages students to build referential connections between visual and verbal representations of the lightning system, then the two groups receiving annotated illustrations (AP and AD) should generate more problem solutions than the two groups receiving illustrations without words (NP and ND). Consistent with this prediction, the ANOVA revealed a significant effect for annotation, $F(1, 68) = 9.27$, $MSE = 2.90$, $p < .01$.

Figure 4 ☐ Mean number of creative problem solutions generated by four groups in Experiment 3.



This result may reflect the fact that the captions and labels summarized respectively the key actions and objects depicted in the illustrations.

Second, if placing illustrations near corresponding text paragraphs fosters building of referential connections, then the two proximate groups (AP and NP) should generate more problem solutions than the two distant groups (AD and ND). The ANOVA revealed no significant effect for placement, $F(1,68) < 3.24$, $MSE = 2.90$, $p < .08$, and thus no statistically significant support for this proposal[2].

Finally, if building a verbal representation depends on both annotating illustrations and placing illustrations near corresponding text, then the AP should perform better than any of the other groups. The ANOVA failed to produce a significant interaction between annotation and placement, $F(1,68) = 2.76$, $MSE = 2.90$, $p = .10$, and thus no support for this proposal. These results suggest that the positive effects of integrated illustrations on problem-solving transfer is caused mainly by annotating illustrations with captions that summarize the major actions in the explanation and labels that point to the major objects in the explanation.

2. These nonsignificant results do not allow us to dismiss proximity of placement of illustrations and text as a possible design variable. Although these analyses failed to yield significant effects or interactions involving proximity of placement of text and illustrations, it should be noted that significant effects would have been obtained if we had used a one-tailed rather than a two-tailed test. In addition, if we examine only the two groups that received annotated illustrations, we can determine whether placing the annotated illustrations near corresponding text (i.e., the AP group), results in better transfer performance than placing the annotated illustrations away from corresponding text (i.e., the AD group). A t test performed on the problem-solving transfer data revealed that the AP group scored significantly higher than the AD group, $t(34) = 2.723$, $p < .01$. Finally, when we conducted an additional analysis of variance on the problem solving data with treatment group (AP, AD, NP, ND) as a single between subjects factor with four levels, we found that the groups differed significantly from one another, $F(3, 68) = 5.089$, $MSE = 2.900$, $p < .01$. Supplemental two-tailed Tukey tests (with alpha at .05) revealed that the AP group scored higher than the NP and ND groups; one-tailed Tukey tests (with alpha at .05) revealed an additional significant difference between the AP and the AD groups. Overall, these analyses suggest that further research is needed to determine the role of proximate versus distant placement of illustrations and text.

DISCUSSION

On the practical side, our results encourage the use of a textbook design principle that consistently improves problem-solving transfer by approximately 50% for inexperienced students. Our research has shown that understanding of scientific text that explains a cause-and-effect system can be greatly improved, especially for less experienced learners, by annotating multi-frame illustrations that portray step-by-step changes in the status of the parts of any to-be-explained system. In spite of their demonstrated effectiveness, annotated multi-frame illustrations are rarely used in science textbooks (Mayer, 1993b). Aspects of the separated illustrations used in our studies can be found in current textbooks wherever illustrations lack succinct captions and labels to guide students' interpretations. These results suggest that modest modifications in the way that illustrations are presented in textbooks could greatly improve students' comprehension.

On the theoretical side, this study provides a successful test of several predictions of a generative theory of textbook design and helps to extend previous results and conclusions (Mayer, 1989b; Mayer & Gallini, 1990) to a new domain. The results suggest that building a useful mental model of a scientific system depends on building integrative connections between verbal information selected from the text and corresponding features of images selected from the illustrations. For example, the integrated group is encouraged to generate a connection between the text, "As raindrops and ice crystals fall through the cloud, they drag some of the air in the cloud downward, producing downdrafts" and an adjacent captioned illustration containing arrows from the top through the bottom of the cloud labeled "downdraft."

In conclusion, we propose that textbooks should be designed in ways that elicit the cognitive processes required for meaningful learning—namely selecting relevant verbal information to build a text base and selecting relevant pictorial information to build an image base, organizing these representations into coherent situation models of the verbal material and of the visual material, and integrating across these two representations of the material. Our research has helped pinpoint the use of annotated illustrations as a way of promoting each of these cognitive processes; that is, our research justifies the inclusion of concise annotations in illustrations.

Although Experiment 3 failed to reveal a significant effect or interaction based on proximity of placement of text and illustrations, it would be inappropriate to conclude that annotated illustrations should not be placed near corresponding text. The results of Experiment 3 should not be used as a justification for dismissing text-illustration proximity as a design variable, but rather should serve as the impetus for additional research on the role of proximity of placement of illustrations and text.

Based on these studies we propose that a set of annotated illustrations can serve three functions corresponding to the cognitive processes required for meaningful learning. First, annotated illustrations can serve as a signal that helps readers select relevant words and images. For example, the third annotated illustration in Appendix A directs the reader's attention toward an image and words representing negative particles at the bottom of a cloud. Second, annotated illustrations can serve as a structural summarizer that helps readers to organize the material into a cause-and-effect system. For example, the five annotated illustrations in Appendix A tell a sequential story in which a change in one frame (such as negative particles moving to the bottom of a cloud in illustration 3) leads to a change in the next frame (negative particles moving from the cloud towards the positive particles on the ground in illustration 4). Third, annotated illustrations can serve as an elaborative cue that helps readers connect visual and verbal representations of the same systems. For example, the drawing of negative particles in the bottom of a cloud in illustration 3 corresponds to the caption and helps the reader understand what the caption means. Each of these proposed cognitive functions of annotated illustrations—as a signal, structural summarizer, and elaborative cue—should be regarded as a research hypothesis requiring further study. □

Richard E. Mayer, Kathryn Steinhoff, Gregory Bower, and Rebecca Mars are with the Department of Psychology of the University of California at Santa Barbara.

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