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# Reducing Cognitive Load by Mixing Auditory and Visual Presentation Modes

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This article reports findings on the use of a partly auditory and partly visual mode of presentation for geometry worked examples. The logic was based on the split-attention effect and the effect of presentation modality on working memory. The split-attention effect occurs when students must split their attention between multiple sources of information, which results in a heavy cognitive load. Presentation-modality effects suggest that working memory has partially independent processors for handling visual and auditory material. Effective working memory may be increased by presenting material in a mixed rather than a unitary mode. If so, the negative consequences of split attention in geometry might be ameliorated by presenting geometry statements in auditory, rather than visual, form. The results of 6 experiments supported this hypothesis.

In recent years, working memory limitations have been identified as a major factor that needs to be considered when instruction is designed. Researchers have used cognitive load theory (e.g., Sweller, 1988, 1989, 1993, 1994) to suggest that many commonly used instructional procedures are inadequate because they require learners to engage in unnecessary cognitive activities that impose a heavy working memory load. Alternatives that reduce extraneous cognitive load have been devised. This research has been generated by the following assumptions concerning our basic cognitive architecture: (a) People have a very limited working memory that is able to hold and process only a few items of information at a time; (b) People have a huge long-term memory that is effectively unlimited in size; (c) Schema acquisition is a primary learning mechanism. Schemata are defined as cognitive constructs that permit people to categorize information in the manner in which it will be used (see Low & Over, 1990, 1992; Low, Over, Doolan, & Michell, 1994; Sweller & Low, 1992). Schemata have the functions of storing information in long-term memory and of reducing working memory load by permitting people to treat multiple elements of information as a single element; (d) Automation of cognitive processes, including automatic use of schemata, is a learning mechanism that also reduces working memory load by effectively bypassing working memory. Automated information can be processed without conscious effort.

A limited working memory is central to this architecture and central to cognitive load theory. Recent work has expanded researchers' knowledge of working memory characteristics and in turn, this work has the potential to expand the instructional techniques generated by cognitive load theory. In this article, we discuss the split-attention effect that previous research has suggested is a cognitive load phenomenon. The split-attention effect occurs when learners are required to divide their attention among and mentally integrate multiple sources of information. Mentally integrating multiple sources of information results in less effective acquisition of information than if learners are presented the same material in a physically integrated form. A physically integrated format reduces the load on working memory.

We suggest that some obstacles associated with working memory limits can be ameliorated by using dual-modality presentation techniques. Some of the recent evidence will be reviewed that indicates the existence of separate working memory channels or processors for auditory (especially verbal) and visual (especially pictorial) information. This work on modality effects has suggested that effective working memory capacity may be enlarged by using multiple channels. If so, the cognitive load associated with split attention may be reduced by presenting information with a dual rather than a unitary mode. We tested this hypothesis in a series of geometry learning experiments.

## Split-Attention Effect

Assume students are presented with a geometry worked example of the type depicted in Figure 1. To understand this

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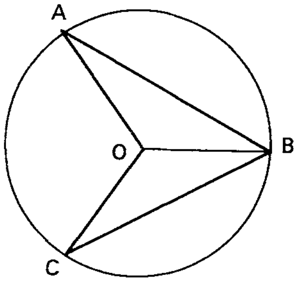
**Problem Statements**

Given: O is the center of the circle.

AB = CB

Prove: $\Delta ABO = \Delta CBO$




**Proof Statements**

1) AO = CO ( radii of the circle)

2) AB = CB ( Given).

3) BO = BO (a common side of the triangles).

4) $\Delta ABO = \Delta CBO$ (SSS Theorem).

*Figure 1.* First worked example in Experiments 1–4. Auditory–visual and simultaneous groups heard the problem and proof statements.

example, students must simultaneously hold in working memory both the diagrammatic information and the information associated with the statements. In addition, the students must mentally integrate the statements with the diagram by holding a statement in memory and searching for the appropriate referents in the diagram. The statements alone are meaningless. Searching for relations between the diagram and statements requires working memory resources. The cognitive load associated with this search is extraneous. It is imposed purely because of the manner in which the material is presented. Furthermore, the cognitive activities associated with searching for relations between the diagram and the statements are irrelevant to schema acquisition.

Many experiments in various areas have demonstrated that the cognitive load consequences of split attention can be eliminated by physically integrating multiple sources of information (Chandler & Sweller, 1991, 1992; Sweller & Chandler, 1994; Sweller, Chandler, Tierney, & Cooper, 1990; Tarmizi & Sweller, 1988; Ward & Sweller, 1990). For example, placing the statements associated with a diagram at appropriate locations on the diagram can dramatically facilitate learning. Eliminating the need to search for relations between the diagram and the statements reduces working memory load thus freeing resources for schema acquisition.

Mayer and his colleagues have provided two lines of research that can be related to the split-attention effect. First, Mayer (1989) and Mayer and Gallini (1990) found that discrete text and unlabeled diagrams were ineffective compared with text and diagrams with appropriately placed labels connecting the text with the diagram. Placing labels on a diagram is likely to be analogous to physically integrating two sources of information. Second, Mayer and Anderson (1991, 1992) found that animation and associated narration were most effective when presented simultaneously rather than sequentially. Mayer and Anderson (1992) labeled this effect the "contiguity principle" (p. 444). There is every reason to suppose that this finding provides a temporal example of split attention.

Physically integrating multiple sources of information facilitates learning by reducing working memory load. Although reducing extraneous cognitive activities that impose a heavy load on working memory is an obvious way of facilitating learning, similar effects should be obtainable by increasing the amount of information that can be held in working memory. In other words, an alternative to reducing working memory load is to increase its effective size. In the next section we discuss some basic characteristics of working memory that may be used to increase the information held in that store.

## Modality Effects

Currently, many memory theorists assume that there are multiple working memory stores, rather than a unitary one. The multiple stores, streams, channels, or processors (the terminology varies) most frequently are associated with auditory or visual processing. For example, Baddeley (1992) suggested a central executive and two supporting systems, a "visual-spatial sketch pad" (p. 556) for dealing with visual images and a "phonological loop" (p. 556) for processing verbal information. The two supporting systems are assumed to process their different types of information in a largely independent fashion. This conception is similar to the dual-coding theory of Paivio (1990), although he places less emphasis on working memory and its limitations.

If the two systems are independent, then the amount of information that can be processed by working memory may, in part, be determined by the modality (auditory or visual) of presentation. The effective size of working memory may be increased by presenting information in a mixed (auditory and visual mode) rather than in a single mode.

In fact, there is evidence that a mixed mode of presentation can increase the amount processed by working memory. Penney (1989) reviewed the evidence for the separate auditory and visual processors hypothesis. She considered research in which material is presented in either an auditory or visual mode. Several lines of evidence for the hypothesis, with the first two being of current interest, were presented.

The first line of research demonstrated that if people are asked to perform two tasks concurrently, performance is improved if the two tasks are presented in different modalities rather than in the same modality. For example, Allport, Antonis, and Reynolds (1972) found that people could attend to and repeat (shadow) continuous auditory speech while processing unrelated visual scenes or sightreading piano music. Additional work indicated that while shadowing, if participants were presented with a series of words to remember, recall was worse if the words were presented in auditory rather than visual mode. (The two auditory messages were presented to different ears.) Hearing words while listening to speech interfered with memory of those words more than did reading them. This result suggests that more capacity is available when two modalities are used rather than one.

The second, related line of research measures the amount people recall when presented with material in a dual rather than a unitary mode. For example, Frick (1984) found that if people were presented visually with a set of items followed by a series of auditory items, recall was better than it was if both sets of items were presented in either the auditory or the visual mode. (The dual mode result was obtained only if participants were required to report the auditory items first.) Findings such as these provide direct evidence of the enhancement of working memory under dual- as opposed to single-mode conditions.

There is other work pointing to the conclusion that working memory can be enhanced by processing in a dual rather than a unitary mode. Brooks (1967) found that if people were given a complex message that needed to be visualized (e.g., a verbal description of a layout that needed to be visualized before it could be understood), recall of the message was enhanced if it was presented solely in auditory mode rather than a combination of auditory and visual modes in which people simultaneously had to listen to and read the message. Inclusion of written material, because it involved visual presentation, apparently interfered with the visualization needed to recall the message. Levin and Divine-Hawkins (1974) presented children with prose passages that they either had to listen to or read. Half of the children were requested to visualize the story content. On a subsequent test of content knowledge, children who listened to the story performed better than those who read it but only under visualization conditions. Visualization improved performance only when the visual system was not required to process the original material.

In combination, the evidence of enhanced working memory capacity under dual-mode conditions is very strong. Although some of the effects have been known for over two decades, as far as we know, they have never been applied in a classroom instructional context. This issue is discussed next.

## Dual Mode Instructional Techniques

If, as suggested by cognitive load theory, working memory limitations must be a primary consideration when instruction is designed, then we have a theoretical rationale for the use of dual-mode instructional techniques. Effective cognitive capacity may be increased if both auditory and visual working memory can be used. Instruction may be enhanced by expanding working memory limits by simultaneous visual and aural presentation of information. That Mayer and Anderson (1991, 1992) found that simultaneous presentation of visual and aural material was superior to successive presentation lends cogency to the argument. Mayer and Anderson, and Paivio (1990), argued that auditory and visual material is processed by separate but interdependent systems.

Consider Figure 1 again; it consists of a diagram and text that need to be integrated before they can be understood. As indicated earlier, mental integration of these two sources of information requires working memory resources, and as a consequence, these resources are unavailable for learning. If working memory resources can be enhanced by dual-mode presentation, then learning may be facilitated. Although the diagram obviously should be presented in its natural, visual mode, the associated statements can be presented aurally just as easily as visually. Simultaneous aural presentation of the statements and visual presentation of the diagram may ameliorate the negative consequences of split attention. A mixed-mode presentation may enhance learning compared to a purely visual mode because of the effective expansion of working memory capacity. In the experiments in this article, we test this hypothesis as an alternative to reducing cognitive load by physically integrating the diagram and statements.

## Experiment 1

Our purpose in Experiment 1 was to compare three modes of presenting geometry worked examples. One group of students (simultaneous group) studied worked examples with the diagram and its associated statements presented visually and heard the statements played from a tape recorder simultaneously. Thus, with reference to Figure 1, this group could, for example, see the diagram, read the first proof statement, "AO = CO (radii of the circle)" while simultaneously hearing this proof statement from the tape recorder. For this group, the visual statements and the diagram constitute a split-attention format and should impose a heavy cognitive load. Alternatively, if students choose to ignore the visual statements and attend to the auditory statements instead, the consequences of split-attention may be eliminated and effective working memory increased because of the use of dual-sensory modes.

Another group of students (visual–visual group) received worked examples in which both the diagram and its associated statements were presented visually only. This group did not hear the statements. Split attention and its concomitant cognitive load was unavoidable for this group. The third group of students (visual–auditory group) studied worked examples in which the diagram was presented visually while they were also listening to the audio tape of its associated statements. The written version of the statements was not available. This group should have an unambiguously reduced cognitive load if, as hypothesized above, students can process the auditory statements while simultaneously attending to the diagram. It was predicted that the performance of the visual–auditory group would be superior to that of the visual–visual group and possibly to that of the simultaneous group (if the simultaneous group chose to attend more to the written than auditory input when dealing with the statements) because of an expansion of effective working memory capacity.

## *Method*

*Participants.* The participants were 30 Year-8 (equivalent to eighth grade in the United States) students from two Wollongong, Australia high schools. The 15 students with the highest grades were selected from one top mathematics class in each high school. These classes were chosen after pilot studies indicated that the students' level of accomplishment in geometry was sufficient to allow them to complete the problem sets after some additional study.

*Procedure.* The day before the experiment, all participants were told that they would be taking a geometry test. No instruction was given concerning the context. All students were tested individually. The procedure consisted of an explanatory, an acquisition, and a test phase. The explanatory phase consisted of an initial, written explanation sheet that provided a maximum 5-min period of instruction to familiarize students with the basic principles of congruent triangles, emphasizing the "side-side-side" (SSS) theorem and the links with circle and square geometry. Students were asked if they had any questions, and questions were answered until students were satisfied that they understood the material.

An "acquisition" or learning phase followed the explanatory phase. In this phase four problems were presented: Two problems were presented as worked examples (see Figures 1 and 2), and two problems similar to the worked examples were presented as repeat problems requiring solution. The first worked example problem (Figure 1) demonstrated relations between congruent triangles and circle geometry, whereas the second (Figure 2) related congruent triangles and the geometry of squares. Study times for the examples as well as solution times and errors for the problems were recorded for each participant.

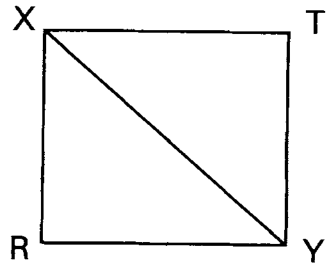
There were three groups of 10 participants per group. Participants were randomly assigned but there were equal numbers of participants from each class in each group. The acquisition treatment differed among the three groups. The participants in the simultaneous group were given the diagram and its associated problem and proof statements on a sheet of paper while they simultaneously heard the statements played from a tape recorder (see Figures 1 and 2). Members of the simultaneous group were informed that they should study the worked example written material and listen to the tape recording carefully until they understood it because the following problem that they had to solve was similar. The participants in the visual–visual group followed the same procedure except that they only had the written materials with no auditory component. The participants in the visual–auditory group were presented with the diagram but not a written version of the statements. While looking at the diagram, the visual–auditory group heard the audio tape of the statements.

Participants in the visual–visual group could study their materials for as long as they wished up to a maximum of 5 min. The simultaneous and visual–auditory groups were required to listen to the tape twice, and the tape playing time determined their study time, which as a consequence, was identical for all participants in these two groups. (There was no study time allocated other than *when the tape was playing.*) Following the first worked example, all groups were given a similar (repeat) problem to solve. An identical procedure was followed for the second worked example and its associated problem.

**Problem Statements**

**Given:** XY is a diagonal of the square XTYR.

**Prove:** $\Delta XTY = \Delta XRY$




**Proof Statements**

1) XT = XR ( sides of the square).
2) YT = YR ( sides of the square)
3) XY = XY ( a common side of the triangles)
4) $\Delta XTY = \Delta XRY$ ( SSS Theorem).

*Figure 2.* Second worked example in Experiments 1–4. Auditory–visual and simultaneous groups heard the problem and proof statements.

While participants were solving the problems, whenever an error was detected, they were informed that an error had been made that should be corrected before proceeding. Participants were allowed multiple solution attempts until the maximum time of 5 min had lapsed. If the correct solution was not obtained during this period, they were shown the solution.

A test phase following the acquisition phase was identical for all groups. The test phase consisted of two sets of two problems each. The first set was similar to the initial problems (Figures 1 and 2) in the acquisition phase. The second set, which consisted of transfer problems, differed from the initial problems in that it required use of the same geometric theorems in a different diagrammatic context (see Figures 3 and 4). Errors were not corrected. If participants provided an incorrect solution they were informed that it was incorrect and were asked to attempt the solution again. Multiple solution attempts were permitted until the correct solution was attained or until the maximum time of 5 min had elapsed. Participants who did not provide a correct solution within the maximum time were not shown the correct solution but were required to commence the next problem. Solution times and errors for all problems were recorded for each participant, with nonsolvers (those who had either not completed solution or who had completed one or more incorrect solutions without providing a correct solution) allocated the maximum time of 300 s. This approach was based on the assumption that nonsolvers' performance was worse than that of any student who correctly solved a problem within the time limit. Participants did not have access to prior materials or work at any stage of the acquisition or test phases.

**Problem Statements**

Given: H is the center of the circle.

LG = KG

Prove: Δ LHG = Δ KHG

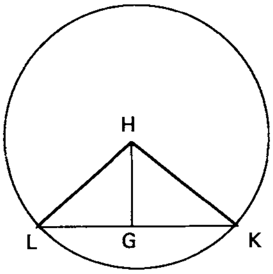



*Figure 3.* First transfer example in Experiments 1–4.

### *Results and Discussion*

The number of seconds taken by each group during both acquisition and test phases was compared. Table 1 indicates the mean number of seconds for solution for the three groups on the acquisition problems. Mean times were based on all participants, regardless of whether the proof was successfully completed. Participants who did not complete a proof were awarded a score of 300 s. It could be argued that awarding maximum time scores to nonsolvers (a) is biased in favor of the present hypotheses insofar as conditions with larger numbers of nonsolvers are inappropriately penalized and (b) is likely to produce markedly skewed distributions. To be conservative, therefore, we reanalyzed all measures in each experiment with nonsolvers' times defined as 10 s more than the highest solver's times for that measure. In all cases, the statistical pattern of results was the same for the two scoring systems.

Because the visual–auditory and simultaneous groups were presented with the same audio-taped recording of the worked examples statements, the time was identical for all participants and so time spent studying worked examples was ignored. Table 1 indicates the mean number of seconds for solution for the three groups on Problems 2 and 4, which were presented as repeat problems (i.e., similar to the worked examples) for all groups. There was a significant difference in the combined times of the two problems between the three groups, $F(2, 27) = 5.92$, $MSE = 5{,}695.27$. (The 0.05 level of significance was used for all analyses except when stated otherwise.) Newman–Keuls tests showed that the visual–auditory group required less time to solve the problems than did the visual–visual group. The simultaneous group also took less time to solve the problems than did the visual–visual group. There was no significant difference between the simultaneous and visual–auditory groups.

Our major question is whether differential acquisition treatments have had consequences during the test phase. If the visual–auditory group had a reduced cognitive load compared with the other two groups, and if as a consequence, learning has been enhanced, we might expect superior test performance by the visual–auditory group.

Table 1 indicates the mean times taken by the three groups to solve the four test problems. For the combined, similar test problems, there was a significant difference between the three groups, $F(2, 27) = 4.81$, $MSE = 4{,}644.53$. Newman–Keuls tests showed that the visual–auditory group spent less time solving the problems than did the visual–visual and the simultaneous groups. There was no significant difference between the simultaneous and the visual–visual groups. On the transfer problems, although the visual–auditory group again solved the problems more rapidly than did the other two groups, the differences were not significant, $F(2, 27) = 2.44$, $MSE = 11{,}105.28$.

Table 1 also indicates the number of nonsolvers during the acquisition and test phases. As can be seen, with the exception of the second transfer problem, the number of nonsolvers is very low, and differences between groups are slight.

In summary, the results of this experiment are consistent with the hypothesis that the use of dual sensory modes reduces cognitive processing load by expanding working memory capacity. A mixed auditory and visual mode of presenting information was more effective than a single (visual) mode.

## Experiment 2

The results of Experiment 1 have demonstrated that the presentation of information in a mixed auditory and visual mode rather than in a single mode, has beneficial effects on learning, presumably through expanding effective working memory capacity. However, it should be noted that the times taken by the visual–visual group to study worked examples were shorter than the times of the other two

**Problem Statements**

**Given:** ABZD is a square.

W is the midpoint of BD

**Prove:** Δ DAW = Δ BAW

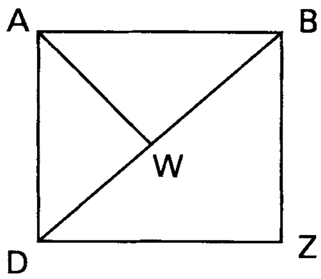



*Figure 4.* Second transfer example in Experiments 1–4.

Table 1
*Mean Seconds Spent Studying or Solving and Number of Nonsolvers for Each Group for Each Problem in Experiment 1*

| Problem and no. of nonsolvers | Group | | |
|---|---|---|---|
| | Visual–Visual | Simultaneous | Visual–Auditory |
| Acquisition phase | | | |
| First worked example | 108.30 | 151.00 | 151.00 |
| First repeat problem | 224.30 | 165.90 | 159.30 |
| Number of nonsolvers | 2 | 1 | 1 |
| Second worked example | 84.90 | 157.00 | 157.00 |
| Second repeat problem | 155.80 | 128.20 | 110.20 |
| Number of nonsolvers | 1 | 0 | 0 |
| Test phase | | | |
| First similar problem | 147.50 | 135.00 | 77.30 |
| Number of nonsolvers | 2 | 1 | 0 |
| Second similar problem | 87.20 | 87.80 | 70.20 |
| Number of nonsolvers | 0 | 0 | 0 |
| First transfer problem | 136.70 | 115.10 | 103.40 |
| Number of nonsolvers | 0 | 0 | 0 |
| Second transfer problem | 202.20 | 189.90 | 133.40 |
| Number of nonsolvers | 4 | 3 | 2 |

*Note.* $n = 10$ for each group.

groups, which were dictated by the audiotaped recording of the worked examples statements. These differences in study times might have contributed to the results obtained, with students in the visual–visual group performing worst because they spent less time studying the worked examples than did students in the other two groups. Experiment 2 was designed to equalize the presentation times of the three groups.

### Method

*Participants.* The participants were 30 Year-8 students from the top mathematics class of a Sydney, Australia metropolitan area high school. This class was chosen after pilot studies indicated that the students' level of accomplishment in geometry was sufficient to allow them to complete the problem sets after some additional study.

*Procedure.* Ten students were randomly assigned to each of three groups. The general procedure was similar to that used in Experiment 1, with the only major difference being in the presentation time of material for the visual–visual group. In Experiment 1, the presentation times for the visual–auditory and simultaneous groups were identical, because they were determined by the tape length, whereas for the visual–visual group, participants determined presentation times. In Experiment 2, the presentation times for the three groups were equal. The time for the visual–visual group was constant for each participant and equal to the time available to participants listening to the auditory tape. Participants, rather than being told to study the worked examples until they were ready, were asked to study the examples for a fixed time. These times were 151 s and 157 s for the first and second worked examples, respectively.

### Results and Discussion

Table 2 indicates the mean number of seconds to solution for the three groups on the four acquisition problems. Mean times were based on all participants, regardless of whether the proof was successfully completed, as in Experiment 1. Participants who did not complete a proof were allocated the maximum time of 300 s.

The primary question examined in Experiment 2 was whether there were significant differences in times to solution as a result of differences in modes of presentation. The difference in times spent on the two repeat acquisition problems was not significant, $F(2, 27) = 1.68$, $MSE = 13{,}490.3$. A significant difference between groups was found on the two similar test problems, $F(2, 27) = 3.74$, $MSE = 1{,}838.39$. Newman–Keuls tests showed that the visual–auditory group spent less time to solve the problems than did the visual–visual group. There were no significant differences between the simultaneous group and the other two groups. On the transfer problems, although the visual–auditory group again solved the problems more rapidly than did the other two groups, the differences were not significant, $F(2, 27) = 2.09$, $MSE = 9{,}718.36$.

Table 2 indicates the number of nonsolvers. As was the case for Experiment 1, there were few nonsolvers.

Overall, the pattern of results of this experiment is similar to that found in Experiment 1 (except that there were no significant differences on the repeat acquisition problems). We were able to conclude that the differences found in both Experiments 1 and 2 were not due to differential acquisition times. Rather, the results were consistent with the hypothesis that presenting the worked examples in a dual mode format expanded effective working memory, thus allowing them to be processed more effectively.

## Experiment 3

Experiments 1 and 2 demonstrated the beneficial effects of presenting instructional material in a mixed auditory and visual mode. This finding is in accordance with the suggestion that effective working memory capacity may be in-

Table 2
*Mean Seconds Spent Studying or Solving and Number of Nonsolvers for Each Group for Each Problem in Experiment 2*

| Problem and no. of nonsolvers | Group | | |
|---|---|---|---|
| | Visual–Visual | Simultaneous | Visual–Auditory |
| Acquisition phase | | | |
| First repeat problem | 150.40 | 154.60 | 93.30 |
| Number of nonsolvers | 1 | 1 | 0 |
| Second repeat problem | 128.00 | 127.20 | 104.40 |
| Number of nonsolvers | 1 | 1 | 0 |
| Test phase | | | |
| First similar problem | 61.10 | 60.60 | 42.30 |
| Number of nonsolvers | 0 | 0 | 0 |
| Second similar problem | 79.90 | 63.10 | 47.20 |
| Number of nonsolvers | 0 | 0 | 0 |
| First transfer problem | 66.80 | 59.20 | 51.60 |
| Number of nonsolvers | 0 | 0 | 0 |
| Second transfer problem | 173.50 | 137.10 | 98.60 |
| Number of nonsolvers | 3 | 2 | 1 |

*Note.* $n = 10$ for each group.

creased if both auditory and visual working memory can be used.

However, the superiority of the visual–auditory presentation mode over the visual–visual presentation mode found in Experiments 1 and 2 is open to an alternative explanation. Assume that in the visual–visual presentation mode it is necessary to hold in working memory information from one source (e.g., the statements) when information from another source (e.g., the diagram) is being processed. Because the statements and the diagram cannot be viewed simultaneously, students are likely to need to read a statement, hold it in working memory, and then attend to the diagram to integrate it with the statement. Although attention may be shifted between sources of information rapidly, nevertheless, it is not possible to look at the diagram and read a statement simultaneously. The act of holding a statement in working memory and then attending to the diagram may be unnecessary for the visual–auditory group, which may be able to attend to both simultaneously. Differences between a visual–visual group and a visual–auditory group may be due entirely to the visual–visual group having to hold material from one source of information in working memory before attending to the other source. This difference may disappear if the visual–auditory group is forced to similarly hold material in working memory.

The cognitive load hypothesis is that working memory capacity is increased with a dual mode of presentation, thus making it easier for students to integrate the diagrams and statements irrespective of whether they are attended to simultaneously or successively. Under this hypothesis, forcing a visual–auditory group to process the information successively, as occurs for a visual–visual group, should not eliminate its advantage. The increased working memory capacity available when using a dual mode of presentation should still be available even if students must hold an auditory statement in memory before viewing the diagram. The increased capacity should still make it easier to mentally integrate the diagram and the statements than a visual–visual presentation.

We designed Experiment 3 to test these two hypotheses by comparing four modes of presenting geometry worked examples: a visual–visual mode and a visual–auditory mode under either simultaneous or sequential presentation conditions. The two simultaneous modes presented the diagram and its associated statements at the same time. The simultaneous modes were identical to the presentation modes given to the visual–visual and visual–auditory groups of Experiment 1. The two sequential modes presented students with the statements and the diagram sequentially, rather than simultaneously, requiring them to hold in working memory information to which they had just attended, by blocking all other relevant information. Thus, for example, when students saw or heard the statements, they could not see the diagram because it was covered. Similarly when they saw the diagram, they could not see or hear the statements. If the difference between groups is due to students having to hold in working memory information they had earlier processed while attending to new information, then there should be a difference between the two simultaneous groups but no difference between the two sequential groups. Alternatively, if the difference is not due to students needing to hold in working memory information they had earlier processed while processing incoming information, but rather is due to increased memory capacity being available when a dual mode of presentation is used, the difference expected for the two simultaneous groups is also to be expected for the two sequential groups.

## *Method*

*Participants.* The participants were 40 Year-8 students from the two top mathematics classes of a Wollongong, Australia high school. These classes were chosen after pilot studies indicated that the students' level of accomplishment in geometry was sufficient to allow them to complete the problem sets after some additional study.

*Procedure.* This experiment again was conducted in three phases. The first phase was the explanatory phase. The procedure and the instructional material for this phase were identical to those used in Experiments 1 and 2.

An acquisition phase followed in which students were given a set of four acquisition problems identical in content to those of Experiments 1 and 2. Again, Problems 1 and 3 were in the form of worked examples, whereas Problems 2 and 4 took the form of similar ("repeat") problems that students were required to solve.

Participants were randomly allocated to one of either two visual–visual groups or two visual–auditory groups, with 10 participants per group. The procedure for the initial worked examples (1 and 3) for the simultaneous visual–visual group and the simultaneous visual–auditory group was the same as for the visual–visual group and the visual–auditory group in Experiment 1. For the sequential visual–visual group, the experimenter showed students the first line of the first worked example (in Figure 1, "Given: O is the center of the circle") with the remaining seven lines and the diagram covered. When the participant had read the line, the experimenter covered all the statements and revealed the diagram. When the participant was ready, the experimenter then showed the second line of the first worked example ("AB = CB") while covering all the other lines, including the first line and the diagram. This procedure of revealing only one line at a time and then the diagram alone was followed until every problem and proof statement line of the worked example was completed. An identical procedure then was used for the second worked example.

For the sequential visual–auditory group the experimenter played the first line of the first worked example problem using a cassette record player and keeping the diagram covered. The diagram was revealed after the first line was played. The participant indicated when he or she was ready for the next line. The diagram was recovered, and the procedure was repeated for the second line. This procedure was followed until every line of the worked example was completed. An identical procedure was followed for the second worked example. The procedure for the repeat acquisition problems and test problems for all four groups was identical to that used in Experiments 1 and 2.

## *Results and Discussion*

Table 3 shows the mean number of seconds to solve each problem. The performance of each group during both acquisition and test phases was compared. The simultaneous visual–visual group spent less time studying their worked examples than did the simultaneous visual–auditory group, which had a fixed time determined by the tape length. The sequential visual–visual group also spent less time studying worked examples than did the sequential visual–auditory group. (Unlike the simultaneous visual–auditory group, the sequential equivalent did not have a fixed study period because the time to study diagrams varied between students.)

Table 3 indicates the mean number of seconds to solution for the four groups on the two repeat problems. A $2 \times 2$ analysis of variance (ANOVA) indicated a significant modality (visual–visual vs. visual–auditory) effect, $F(1, 36) = 11.18$, $MSE = 16{,}800.11$, with the visual–auditory groups requiring less time to solve the two repeat problems. There was no significant effect that was due to presentation sequence (simultaneous vs. sequential) and no significant modality by presentation sequence interaction, both $Fs < 1$. The lack of a significant interaction suggests that the advantage of the visual–auditory procedure occurs irrespective of whether the material is presented simultaneously or successively. Specifically, successive presentation of the auditory and visual material has not destroyed the advantage of the visual–auditory procedure.

With respect to the test phase, the differences between conditions on the two similar problems, also indicated a significant modality effect, $F(1, 36) = 12.88$, $MSE = 5{,}627.56$; again this was due to a visual–auditory advantage. There was no significant effect that was due to presentation

Table 3
*Mean Seconds Spent Studying or Solving and Number of Nonsolvers for Each Group for Each Problem in Experiment 3*

| Problem and no. of nonsolvers | Group | | | |
|---|---|---|---|---|
| | Simultaneous | | Sequential | |
| | Visual–Visual | Visual–Auditory | Visual–Visual | Visual–Auditory |
| Acquisition phase | | | | |
| First worked example | 111.40 | 151.00 | 159.50 | 251.80 |
| First repeat problem | 180.60 | 128.40 | 206.50 | 101.80 |
| Number of nonsolvers | 2 | 0 | 4 | 0 |
| Second worked example | 74.10 | 157.00 | 144.90 | 224.90 |
| Second repeat problem | 163.70 | 88.30 | 156.80 | 115.00 |
| Number of nonsolvers | 2 | 0 | 2 | 0 |
| Test phase | | | | |
| First similar problem | 113.00 | 63.80 | 100.10 | 47.70 |
| Number of nonsolvers | 0 | 0 | 0 | 0 |
| Second similar problem | 92.40 | 48.50 | 76.90 | 52.10 |
| Number of nonsolvers | 0 | 0 | 0 | 0 |
| First transfer problem | 72.30 | 54.90 | 89.20 | 65.40 |
| Number of nonsolvers | 0 | 0 | 0 | 0 |
| Second transfer problem | 131.10 | 100.50 | 162.80 | 108.40 |
| Number of nonsolvers | 2 | 0 | 0 | 0 |

*Note.* $n = 10$ for each group.

sequence and no significant interaction, both $Fs < 1$. Again, the fact that we did not find a significant interaction suggests that using the visual–auditory procedure is advantageous even when information from the two modes cannot be processed simultaneously. Analyses of the differences between conditions on the two transfer problems indicated an effect that was due to modality, favoring the visual–auditory group, $F(1, 36) = 3.63$, $MSE = 10{,}965.57$, $p < .05$ (one-tailed), but no effect that was due to presentation sequence, $F(1, 36) = 1.02$, $MSE = 10{,}965.57$, nor an interaction effect ($F < 1$).

Table 3 indicates the number of nonsolvers for each problem. As can be seen, there were very few nonsolvers.

The results of this experiment demonstrated that regardless of whether the two sources of information (diagram and statements) were altered to simultaneous or successive presentation, a dual mode of presentation was superior. This finding suggests that the advantage of the dual mode over the single mode of presentation is not due to having to hold material from one source of information in working memory before attending to the other source in single mode processing. The superiority of the sequential visual–auditory group over the sequential visual–visual was just as marked as the superiority of the simultaneous visual–auditory group over the simultaneous visual–visual group. On the basis of these results, the advantage of the dual mode over the single mode of presentation is more likely to derive from an expanded memory capacity rather than from the need for visual–visual students to hold information from the statements in working memory before attending to the diagram.

It might be noted, that on the surface, the results of Experiment 3 might appear to contradict those of Mayer and Anderson (1991, 1992) who found that simultaneous auditory and visual presentation was superior to successive. In fact, cognitive load theory can explain both sets of results (R. E. Mayer, personal communication, May 2, 1994). In the Mayer and Anderson studies, relatively large blocks of animation and narration were presented successively rather than in the line-by-line presentation of Experiment 3. These large blocks are likely to have imposed a heavy working memory burden, thus resulting in poor performance by the successive-presentation groups.

## Experiment 4

The results of Experiment 3 suggest that the superiority of the mixed auditory and visual presentation over the single visual mode presentation found in Experiments 1 and 2 was not due solely to the suggestion that, in the visual mode but not in the mixed auditory and visual modes of presentation, students need to hold in working memory information required to process new information. Rather, the results are more likely to be due to an expanded effective working memory capacity. However, as in Experiment 1, the study times for the single-mode groups were shorter than they were for the corresponding mixed auditory and visual groups. We designed Experiment 4 to equalize study times by allowing students in the visual–visual groups the same time to go through the worked examples as was taken by the corresponding auditory groups.

### Method

*Participants.* The participants were 40 Year-8 students from the top two classes of a Sydney, Australia metropolitan area high school. These students were chosen after pilot studies indicated that their level of accomplishment in geometry was sufficient to allow them to complete the problem sets after some additional study.

*Procedure.* The general procedure was similar to that used in Experiment 3, with the major difference being in the acquisition presentation times of worked examples. In Experiment 3, the presentation times of materials for the two visual–auditory groups were not identical to those of the two visual–visual groups. In this experiment, for the simultaneous presentation condition the time for the visual–visual group was constant for each participant and was equal to the time available to participants listening to the auditory tape (as in Experiment 2). For the sequential presentation condition, the time available to the visual–visual group to read each statement was identical to the auditory tape playing time for that statement. The time available to study the diagram after each statement was heard or read was determined by the time required by the first participant in the visual–auditory group. All other participants were allocated the same times for each view of the diagram. In this manner, study times were equalized for each worked example for both groups.

### Results and Discussion

The performance of each group during both the acquisition and the test phases was compared. Table 4 shows the mean time spent on each problem by each group.

With respect to the two repeat problems, a $2 \times 2$ ANOVA indicated no significant effects: modality, $F(1, 36) = 2.67$, $MSE = 7{,}182.43$; presentation sequence and interaction, both $Fs < 1$. With respect to the test phase, the differences between conditions on the two similar test problems indicated a significant modality effect, $F(1, 36) = 7.31$, $MSE = 2{,}956.58$, with the visual–auditory groups demonstrating superiority over the visual–visual groups. There was no effect that was due to presentation sequence (simultaneous vs. sequential) and no significant interaction, both $Fs < 1$, thus indicating that the use of a sequential presentation procedure did not eliminate the modality effect. The differences between conditions on the two transfer problems also indicated a significant modality effect, $F(1, 36) = 5.29$, $MSE = 8{,}934.75$, but no effects that were due to presentation sequence nor to the interaction, both $Fs < 1$, thus replicating the results for the similar test problems.

Table 4 indicates the number of nonsolvers for each problem. As for the previous experiments, there were very few nonsolvers, and differences between groups were slight.

The results of this experiment are consistent with those obtained in Experiment 3. Again, the results indicate the beneficial effects of presenting instructional material in a mixed auditory and visual mode. The fact that we did not obtain a significant interaction indicates that the modality

Table 4
*Mean Seconds Spent Studying or Solving and Number of Nonsolvers for Each Group for Each Problem in Experiment 4*

| Problem and no. of nonsolvers | Group: Simultaneous Visual–Visual | Simultaneous Visual–Auditory | Sequential Visual–Visual | Sequential Visual–Auditory |
|---|---|---|---|---|
| Acquisition phase | | | | |
| First worked example | 151.00 | 151.00 | 210.00 | 210.00 |
| First repeat problem | 128.10 | 98.10 | 119.60 | 112.50 |
| Number of nonsolvers | 2 | 1 | 0 | 0 |
| Second worked example | 157.00 | 157.00 | 190.00 | 190.00 |
| Second repeat problem | 129.20 | 91.10 | 117.60 | 105.20 |
| Number of nonsolvers | 1 | 0 | 1 | 0 |
| Test phase | | | | |
| First similar problem | 74.10 | 50.90 | 71.80 | 47.20 |
| Number of nonsolvers | 0 | 0 | 0 | 0 |
| Second similar problem | 65.10 | 45.20 | 75.50 | 50.20 |
| Number of nonsolvers | 0 | 0 | 0 | 0 |
| First transfer problem | 76.20 | 50.50 | 71.50 | 51.20 |
| Number of nonsolvers | 0 | 0 | 0 | 0 |
| Second transfer problem | 172.70 | 120.50 | 166.90 | 127.60 |
| Number of nonsolvers | 1 | 1 | 2 | 1 |

*Note.* $n = 10$ for each group.

effect is probably due to increased working memory capacity under dual-mode presentation conditions rather than to sequential or simultaneous presentation of information.

## Experiment 5

The previous four experiments, which were based on geometry worked examples, suggest that effective cognitive capacity may be increased if both auditory and visual working memory can be used. Results indicated that a mixed auditory and visual mode presentation was superior to a single visual mode presentation when the problem consisted of a diagram and the solution consisted of text. However, the theory used to generate the experiments is quite general and should not be restricted to instructional materials in which one source of information is a diagram and the other consists of text.

We designed Experiment 5 to test the mixed-mode effect with mathematical problems in which both sources of information consisted of verbal statements, rather than a diagram and statements. Four modes of presenting worked examples concerning the dimensions of a rectangle were compared. Whereas the verbal–written mode presented both the problem information and the solution statements in a visual sentence format, the verbal–auditory mode presented the problem information in a visual sentence format and the solution statements aurally from a tape recorder. The diagram–written mode presented the problem information as a diagram and the solution statements in written form, whereas the diagram–auditory mode presented the problem information as a diagram and the solution statements aurally. In accordance with cognitive load theory and the results of the four experiments reported earlier, we predicted that the performance of students who learned under the verbal–auditory and the diagram–auditory conditions would be superior to that of students who learned under the verbal–written and diagram–written conditions, respectively.

### *Method*

*Participants.* The participants were 40 Year-4 students (equivalent to US 4th graders) randomly chosen from a Sydney, Australia metropolitan area primary public school. None had any prior, formal training in geometry.

*Procedure.* All students were tested individually. The procedure consisted of three phases. The explanatory phase, with an initial, written explanatory sheet, provided a maximum 5 min period of instruction to familiarize students with the basic principles of rectangles with an emphasis on the perimeter.

An "acquisition" or learning phase followed the explanatory phase. Two similar problems were presented as worked examples (see Figure 5 for an example). The worked examples were identical in format, with the only difference being in the numerical values used. Each of the worked examples consisted of two sources of information: (a) the problem presented either in diagrammatic or written verbal format and (b) a set of statements referring to relations between elements of the problem presented either visually (written) or aurally (from a tape recorder). Attention had to be divided between the problem and the set of statements. The time for the four groups was constant for each participant and equal to the time available to participants listening to the auditory tape. All students were required to study each worked example for a fixed period of 60 s before going on to the next similar ("repeat") problem. A maximum of 3 min was allowed to solve each problem. Students were informed of any incorrect solutions and were allowed additional attempts until the maximum time had elapsed. If the correct solution was not obtained during this period, the student was shown the solution.

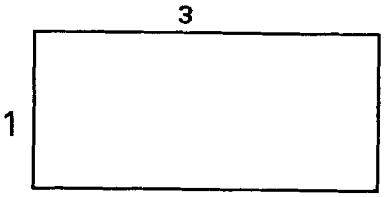
Students were assigned randomly to the four groups, with 10 students per group. Each group was given the same materials with different presentation formats. The verbal–written group received the problems and the set of statements both in a visual sentence format. The verbal–auditory group received the problems visually

Problem Statements

The length of a rectangle is 3 cm. Its width is 1 cm.

What is the perimeter

of the rectangle?




Answer

Length + width = 3 cm + 1 cm

= 4 cm

The perimeter = 4 cm x 2

= 8 cm

*Figure 5.* A worked example used in Experiment 5. The verbal–written group received the problem and the answer both in visual sentence format. The verbal–auditory group received the problem visually in sentence form and the answer aurally from a tape recorder. The diagram–written group received the problem as a diagram and the answer in written form. The diagram–auditory group received the problem as a diagram and the answer aurally from a tape recorder.

in sentence form and the set of statements aurally from a tape recorder. The diagram–written group received the problems as a diagram and the statements in written form. The diagram–auditory group received the problems visually and the statement aurally from a tape recorder.

The test phase following the acquisition phase was identical for all groups. The test phase consisted of two sets of two problems each. The first set was similar to the worked example problems in the acquisition phase. The second set, which consisted of transfer problems, was different from the worked example problems in that it required using the same geometric procedures in a different context (see Figure 6). Each problem consisted of a verbal problem statement, a diagram, and the question. During the test phase of the experiment, participants did not have access to previous work carried out during any phase of the experiment or to previously seen example problems.

## *Results and Discussion*

The mean number of seconds taken by each group to solve the problems during both acquisition and test phases were compared. Mean times were based on all participants, regardless of whether the problem was successfully completed. Participants who did not complete a problem were allocated the maximum time of 180 s.

Table 5 indicates the mean number of seconds to solution for the four groups on the two repeat problems. A 2 × 2 ANOVA indicated significant main effects: problem presentation format, $F(1, 36) = 5.93$, $MSE = 4{,}925.09$, indicating that a diagrammatic presentation was superior to a verbal presentation; statement presentation format, $F(1, 36) = 17.88$, indicating that an auditory presentation of the statement was superior to a written presentation. There was no significant interaction ($F < 1$) suggesting that auditory statements resulted in an equivalent improvement whether paired with written or diagrammatic problems.

With respect to the test phase, if the two groups, verbal–auditory and diagram–auditory, had a reduced cognitive load compared with the other two groups and if, as a consequence, learning has been enhanced, we might expect superior test performance by these two groups giving a similar pattern of results to the acquisition problems. Table 5 indicates the mean number of seconds to solution per group for the two similar and the two transfer problems.

The differences between conditions on the two similar problems indicated significant main effects: problem presentation format, $F(1, 36) = 15.32$, $MSE = 725.90$; statement presentation format, $F(1, 36) = 9.21$. There was no significant interaction $F(1, 36) = 1.18$.

The differences between conditions on the two transfer problems also indicated significant main effects: problem presentation format, $F(1, 36) = 5.51$, $MSE = 2{,}072.48$; statement presentation format, $F(1, 36) = 4.52$. There was no significant interaction ($F < 1$).

Table 5 indicates the number of nonsolvers. As was the case for the previous experiments, there were few nonsolvers.

In summary, the results of this experiment demonstrate the superiority of auditory solution statements over written solution statements regardless of whether problem information is presented in written or diagrammatic form. This finding, together with the results of the previous experiments can be best explained with cognitive load theory. When multiple sources of information must be mentally

Problem Statements

The length of a rectangle is 4 cm. Its width is half of its length.

What is the perimeter

of the rectangle?

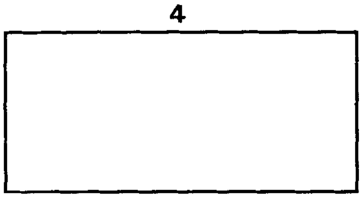



*Figure 6.* A transfer example used in Experiment 5.

Table 5
*Mean Seconds Spent Studying or Solving and Number of Nonsolvers for Each Group for Each Problem in Experiment 5*

| Problem and no. of nonsolvers | Group | | | |
|---|---|---|---|---|
| | Verbal–Written | Verbal–Auditory | Diagram–Written | Diagram–Auditory |
| Acquisition phase | | | | |
| First worked example | 60.00 | 60.00 | 60.00 | 60.00 |
| First repeat problem | 154.50 | 126.00 | 146.00 | 84.00 |
| Number of nonsolvers | 6 | 4 | 6 | 0 |
| Second worked example | 60.00 | 60.00 | 60.00 | 60.00 |
| Second repeat problem | 110.70 | 54.00 | 73.80 | 33.30 |
| Number of nonsolvers | 3 | 0 | 1 | 0 |
| Test phase | | | | |
| First similar problem | 53.70 | 39.00 | 32.10 | 22.60 |
| Number of nonsolvers | 0 | 0 | 0 | 0 |
| Second similar problem | 48.40 | 28.00 | 27.40 | 20.30 |
| Number of nonsolvers | 0 | 0 | 0 | 0 |
| First transfer problem | 58.00 | 55.00 | 47.50 | 41.90 |
| Number of nonsolvers | 0 | 0 | 0 | 0 |
| Second transfer problem | 79.40 | 42.30 | 46.60 | 31.10 |
| Number of nonsolvers | 1 | 0 | 0 | 0 |

*Note.* $n = 10$ for each group.

integrated before they can be understood, working memory resources are not available for learning. However, if the two sources of information are presented in different modalities, then learning may be facilitated by an expansion of available working memory capacity.

## Experiment 6

The previous five experiments demonstrated the beneficial effects of presenting instructional material in a mixed auditory and visual mode. This finding supports the suggestion that working memory capacity can be increased with a dual-presentation mode. However, the superiority of the mixed mode over the purely visual mode found in the previous experiments is open to an alternative explanation. It might be argued that, in general, a visual mode of presentation is more demanding than an auditory mode. For example, reading may be a more cognitively demanding task than listening, perhaps because the reading process may not have been automated. If so, the excessive cognitive load that may occur when reading statements may be due to reading difficulties rather than to the fact that reading solution statements uses the same modality as reading problem statements.

Experiment 6 was designed to test the possibility that the results of the prior experiments may be due to visual processes, such as reading, being more cognitively demanding than the listening process. With similar materials to those used in Experiment 5, we compared two modes of presentation: a visual–visual mode and an auditory–auditory mode. Whereas the visual–visual mode presented both the problem information and the solution statements in a visual sentence format, the auditory–auditory mode presented the identical information aurally, from a tape recorder. We hypothesized that if the results of the previous experiments were due to reading difficulties by students required to read rather than to hear text, then the performance of the auditory–auditory group should be superior to that of the visual–visual group.

### Method

*Participants.* The participants were 20 Year-4 students randomly chosen from a Sydney, Australia metropolitan area public primary school. None had any prior formal training in problems dealing with the dimensions of a rectangle.

*Procedure.* All students were tested individually. The procedure consisted of three phases. The explanatory phase was identical to that used in Experiment 5. An "acquisition" or learning phase followed. Two similar problems were presented as worked examples (Figure 7 provides an example). The worked examples were identical in format, with the only difference being in the numerical values used. As was the case in Experiment 5, each of the worked examples consisted of two sources of information: the problem and a set of statements referring to relations between elements of the problem. Attention had to be divided between the problem and the set of statements. Both the problem and the associated set of statements were presented either entirely aurally or entirely visually.

All students were required to study each worked example for a fixed period of 55 s before proceeding to the following similar problem. A maximum of 3 min was allowed for each similar problem. Students were informed of any incorrect solutions and allowed additional attempts until the maximum time had lapsed. If the correct solution was not obtained during this period the students were shown the solution.

Students were assigned randomly to the two groups, with 10 students per group. Each group was given the same materials with different presentation formats. The auditory–auditory group received the worked example problems and statements from a tape recorder. The visual–visual group read the worked example problems and the set of statements from the written sheets.

**Problem Statements**

The width of a rectangle is 1 cm. Its length is 3 cm.

What is its perimeter?

**Answer**

$$1 \text{ cm} + 3 \text{ cm} = 4 \text{ cm}$$

**The perimeter** $= 4 \text{ cm} \times 2$

$= 8 \text{ cm}$

*Figure 7.* A worked example used in Experiment 6. The auditory–auditory group heard the problem and the answer.

The test phase following the acquisition phase was identical for both groups. The test phase consisted of two sets of two problems. The first set was similar to the worked example problems in the acquisition phase. The second set, which consisted of transfer problems, was different from the worked example problems in that it required the students to use the same knowledge of perimeter of a rectangle in a different context (e.g., "The perimeter of a rectangle is 10 cm. Its length is 3 cm. What is its width?"). During the test phase of the experiment participants did not have access to previous work carried out during any phase of the experiment or to previously seen example problems. No diagram was provided in this experiment during either the acquisition or test phases.

### *Results and Discussion*

Table 6 shows the mean number of seconds to solve each problem and the number of nonsolvers. The performance of each group during both acquisition and test phases was compared. A $t$ test indicated a significant difference between the two groups in the acquisition phase. The visual–visual group spent less time solving their repeat problems than did the auditory–auditory group, $t(18) = 2.12$, $SE = 37.08$.

Our major question was whether differential acquisition treatments have consequences during the test phase. If the listening process is less cognitively demanding than the reading process, then we would expect superior test performance for the auditory–auditory group.

Table 6 indicates the mean number of seconds to solution per group for each of the two similar and the transfer problems. The difference between groups on the two similar problems was not significant, $t(18) = 0.90$, $SE = 28.89$. Similarly, there was no significant difference between groups on the transfer problems, $t(18) = 0.21$, $SE = 31.43$. Nevertheless, as was the case in the acquisition phase, the times taken to solve both the similar and transfer test problems were actually shorter for the visual–visual group than for the auditory–auditory group.

Table 6 indicates the number of nonsolvers. There were few nonsolvers except for the transfer tasks, which most students found insoluable.

In summary, the results of Experiment 6 demonstrate that for the students included, reading problem and solution statements is no more cognitively demanding than is listening to the same information. In fact, the reverse may be true: Although test differences were not found to be significant, the results provide some indication that listening to problem statements and solution statements requires more cognitive resources than does reading the same information. A significant difference in solving repeat problems during acquisition favored the visual–visual group. It also should be noted that these results were obtained with Year-4 students whose reading skills are likely to be substantially inferior to those of the Year-8 students who participated in Experiments 1–4.

## General Discussion

We began by indicating that basic research into the characteristics of working memory has suggested that this processing system is divided into at least two partially independent subprocessors: an auditory system devoted heavily to language and a visual system for handling images, including writing. Because both systems can be used simultaneously, limited working memory capacity might be effectively increased if information that must be stored or simultaneously processed is presented in a manner that permits it to be divided between the two systems, rather than processed in one system alone. As a consequence, informationally equivalent material that may be difficult to process in a purely visual manner may be more easily handled if it can be presented partially in both modalities.

This research into working memory modality effects can

Table 6
*Mean Seconds Spent Studying or Solving and Number of Nonsolvers for Each Group for Each Problem in Experiment 6*

| Problem and no. of nonsolvers | Group: Auditory–Auditory | Group: Visual–Visual |
|---|---|---|
| Acquisition phase | | |
| First worked example | 55.00 | 55.00 |
| First repeat problem | 144.20 | 93.60 |
| Number of nonsolvers | 5 | 0 |
| Second worked example | 55.00 | 55.00 |
| Second repeat problem | 79.30 | 51.30 |
| Number of nonsolvers | 2 | 1 |
| Test phase | | |
| First similar text problem | 44.60 | 43.10 |
| Number of nonsolvers | 0 | 0 |
| Second similar text problem | 60.40 | 35.90 |
| Number of nonsolvers | 2 | 0 |
| First transfer text problem | 170.40 | 170.10 |
| Number of nonsolvers | 8 | 8 |
| Second transfer text problem | 158.70 | 152.40 |
| Number of nonsolvers | 6 | 8 |

*Note.* $n = 10$ for each group.

be applied directly to the cognitive load consequences of split attention. If students are required to split their attention among multiple sources of information that must be mentally integrated before they can be understood, learning may be inhibited because the act of mental integration requires working memory resources that consequently are unavailable for schema acquisition and automation. Alternatively, if effective working memory can be increased by having two sources of information presented via different modalities, the negative effects of split attention may be ameliorated. This hypothesis was tested in this article.

In Experiments 1 and 2, we compared the consequences of presenting students with geometry worked examples in which the statements accompanying the diagram were presented in written mode, in auditory mode, or in both modes. Learning was comparatively enhanced by the auditory mode of presentation in both experiments, thus supporting the suggestion that working memory capacity was increased by a dual-presentation mode. In Experiments 3 and 4, we tested the possibility that the superiority of the mixed mode of presentation was due to the fact that auditory statements can be processed simultaneously with the diagram, whereas written statements have to be held in memory while attention is switched from the statements to the diagram. In both experiments, results indicated that the mixed mode of presentation was superior even when both groups were forced to hold the information contained in the statements in working memory before sighting the diagram. In Experiment 5, we tested the hypothesis that a modality effect could be obtained even when both sources of information consisted of statements rather than a diagram and statements. A mixed mode of presentation proved superior irrespective of whether information concerning the dimensions of a rectangle was presented in diagrammatic or written statement form. Experiment 6 provided evidence that the results of the previous experiments were unlikely to be due to students simply finding listening an easier task than visually based processes such as reading. There were few differences between a group required to listen to information as opposed to a group reading the same material. Minor differences that were obtained favored the reading group.

It is doubtful that reading skills reflect a significant factor in the results of these experiments. The number of words that required reading was minimal. Furthermore, when reading, students could read the material as many times as they wished and, in Experiments 1 and 3, for as long as they wished. We might expect that any reading slowness or other minor difficulties should be overcome with multiple readings. In contrast, the auditory groups only were able to hear the material twice.

It also should be noted that the positive effects of a visual–auditory over a visual–visual mode of presentation extended to transfer problems as well as to problems similar to those used in the acquisition phase. Although our procedure of using multiple replications with small samples resulted in only some of the transfer comparisons yielding significant effects, all of the differences in Experiments 1–5 favored the visual–auditory mode of presentation (see Tables 1–5). We conclude that the visual–auditory presentation of the information may have had the potential to permit a deeper understanding of the material being studied than did the visual–visual presentation modes, assuming that speed of solving transfer problem is indicative of depth of understanding.

The materials used in the experiments required coordination between auditory and visual components. Coordination between components can be assumed to be governed by the central executive (Baddeley, 1992), which has been the subject of recent research. Logie, Gilhooly, and Wynn (1994) found evidence that disruption of the central executive could severely disrupt working memory performance. Yee, Hunt, and Pellegrino (1991) found evidence that the ability to coordinate perceptual and verbal information, which is a central executive function, was distinct from perceptual and verbal performance alone. If coordinating perceptual and visual information requires a central executive function that can be readily disrupted, it could be argued that the visual–auditory groups in the present experiments should perform worse than the visual–visual groups, rather than better. In fact, coordination of the diagrammatic and verbal information is just as important irrespective of the presentation modality of the verbal information. The diagram and statements must be coordinated before a worked example can be understood irrespective of whether the statements are presented visually or aurally. If so, the act of coordination should make equal demands of the central executive under both presentation modes. Our suggestion is that more working memory resources are available for coordination when a dual-presentation mode is used because more information is likely to be held in both auditory and visual working memory rather than in just one.

As indicated earlier, the experiments were generated by a combination of cognitive load theory and recent theories and findings concerning basic working memory processes. In turn, that the results accord with the hypotheses strengthens the theories that generated the hypotheses. Specifically, we see these results as supporting the suggestion that (a) consideration of limited working memory is a major determinant of instructional design success, and (b) working memory capacity can be increased with a dual-presentation mode.

Although the results are consistent with cognitive load theory, we have not attempted to measure cognitive load directly. Our primary aim was to use the theory to generate experiments providing direct instructional implications. We believe our experiments have succeeded in this aim. Nevertheless, the possibility of plausible alternative explanations of our results should not be discounted. Further work could include subjective measures of cognitive load and efficiency measures of instructional conditions such as those introduced recently by Paas and Van Merrienboer (1993, 1994).

There now is considerable work demonstrating the importance of cognitive load in instructional design and the presentation of information in general (e.g., Carroll, 1994; Paas, 1992; Paas & Van Merrienboer, 1994; Pierce, Duncan, Gholson, Ray, & Kamhi, 1993; Robins & Mayer, 1993; Trafton & Reiser, 1993; Van Merrienboer & De Croock, 1992). This work covers various procedures and materials and, we believe, suggests that instructional design that does not emphasize cognitive load factors is likely to be deficient. The current work is intended as an extension of cognitive load factors in instructional design. It differs in that whereas previous researchers considered techniques designed to reduce extraneous cognitive load, we also considered techniques for increasing effective working memory. Both procedures can be highly effective.

In the current series of experiments, we have obtained results suggesting that when students must split their attention between multiple sources of information that require mental integration, cognitive resources available for learning can be increased by presenting some of the verbal material in auditory rather than written form. Frequently, of course, it is not possible to present material in an auditory mode. Under these conditions, split attention can be reduced by physically integrating disparate sources of information (e.g., see Chandler & Sweller, 1991; Sweller et al., 1990). Nevertheless, the availability of computer-based educational technology that can handle auditory material has increased markedly in recent years. Our results provide theoretically motivated and empirically tested techniques for the use of this technology. In more general terms, we believe that cognitive load theory can provide a useful guide to instructional design under an increasing number of circumstances.

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