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Integrating Visual and Verbal Knowledge During Classroom Learning with Computer Tutors

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Abstract

Prior research in multimedia learning has demonstrated that materials that present visual and verbal information in an integrated, rather than split-source, format can support successful learning outcomes. These benefits often are attributed to reductions in cognitive load during learning; however, linking visual and verbal sources in materials also may support cognitive processes that coordinate visual and verbal knowledge. We tested the effects of integrated visual-verbal learning materials by implementing a diagram-based version of an intelligent tutoring system for geometry in 10th grade classrooms. Compared to a standard split-source version of the tutor, students working with the integrated tutor performed better on far transfer tasks that tested deep understanding of connections between conceptual geometry principles and diagram features. Findings demonstrate that integrated materials support development of coordinated visual-verbal knowledge during learning.

Keywords: diagrams; geometry; integration; visual representations; learning; transfer.

Introduction

Previous work in multimedia learning has shown that the presentation format of visual and verbal learning materials can influence student performance (Butcher, 2006; Hegarty & Just, 1993; Kalyuga, Ayres, Chandler, & Sweller, 2003; Kalyuga, Chandler, & Sweller, 2000; Mayer, 2001; Moreno & Mayer, 1999). One formatting issue deals with the level of coordination between visual and verbal sources of information. Visual and verbal information can be integrated (e.g., where short text descriptions are embedded in a diagram) or presented in a separate, "split-source" format (e.g., where paragraph text is physically separate from an unlabeled diagram). Past research has found that integrated materials support students' memories for and understanding of to-be-learned information (Hegarty & Just, 1993; Moreno & Mayer, 1999).

Our work is studying the impact of integrated representations that closely link visual and verbal information in an intelligent geometry tutoring system on students' problem solving performance and deep understanding, when students use the integrated materials during practice in real classrooms. In this paper, we present

the results of two studies comparing the effects of an (experimenter-designed) integrated version of the Geometry Cognitive Tutor to a standard, split-source version. We hypothesized that integrated materials would support students' coordination of visual and verbal information during practice, leading deep learning and improved performance on far transfer tasks.

Visual-Verbal Integration During Learning

Studies with varied multimedia materials have found that even relatively simple forms of coordination between visual and verbal information can impact student learning. Studies have shown benefits in the temporal association of visual and verbal information, where presenting visual and verbal sources at the same time leads to better learning than presenting them at different times (Mayer & Anderson, 1992; Mayer, Moreno, Boire, & Vagge, 1999). Benefits have also been found for spatial association, where learning is supported by placing visual and verbal materials in close physical proximity or integrating them into a single, combined representation (Hegarty & Just, 1993; Moreno & Mayer, 1999). One proposed rationale for these benefits is that temporal/spatial coordination reduces cognitive load demands associated with working memory maintenance and visual search (Mayer, 2001). The reduction in cognitive effort needed to find and maintain multiple sources of information allows students to engage in deeper processing.

However, another possible interpretation of the learning benefits found when materials integrate or coordinate visual and verbal information is that the depiction of close, explicit connections between visual and verbal representations prompts the learner to consider and process connections between visual and verbal information. Thus, integrated representations may support construction of representations that include connections between visual and verbal knowledge components. Although precise specification of these internal representations or processes is beyond the scope of this paper, our proposal builds upon existing models of multimedia learning that assume distinct internal representations are formed from visual and verbal information, and that cognitive processes operate between

these representations (e.g., Mayer, 2001; Schnotz & Bannert, 2003).

There is some evidence that supporting the active coordination of visual and verbal information during learning can promote students' understanding, especially with complex materials. A recent study found that although integrated materials support learning better than split-source materials, learning can be further promoted by materials that require students to actively create an integrated, external representation using initially split-source materials (Bodemer, Ploetzner, Feuerlein, & Spada, 2004). Other research has shown that mental model development can be supported when diagrams prompt learners to generate inferences that integrate information during learning (Butcher, 2006). These results provide initial evidence that learning can be supported by presenting students with materials that promote visual-verbal integration processes.

Cognitive Load: Limitations for Classrooms

A number of studies have attributed the learning benefits associated with integrated materials to reductions in cognitive load during learning (e.g., Chandler & Sweller, 1991, 1992; Sweller & Chandler, 1994). A cognitive load approach suggests that integrated materials reduce the extraneous effort needed to map between visual and verbal information, allowing more cognitive effort to be focused on deeper processing. Cognitive load effects have been shown to be powerful in laboratory studies (Chandler & Sweller, 1991, 1992; Sweller & Chandler, 1994). However, cognitive load effects may be most relevant for novices who have limited exposure to learning materials. Several studies have shown that increasing learners' existing knowledge reduces cognitive load effects during learning (e.g., Kalyuga et al., 2003; Kalyuga et al., 2000). The impact of materials that reduce cognitive load demands appears to fade with time, as learners develop increasing skills and expertise.

Although it may not be the case that classroom learners typically achieve expert-level performance, recent research has demonstrated that powerful cognitive load-style effects that have been identified in laboratory research are difficult to produce in a classroom environment (Olina, Reiser, Huang, Lim, & Park, 2006). Olina et al. found no significant effects on performance or perceived mental effort when using two laboratory-studied effective cognitive load treatments (problem-type and presentation sequence) in a real classroom setting. Although this study may have suffered from poor overall student performance, it suggests that cognitive load effects may be weak, if not absent, following practice in classroom settings. Recent research in intelligent tutoring (e.g., McLaren, Lim, Gagnon, Yaron, & Koedinger, 2006) also has found that laboratory-identified effects do not affect student performance when interventions are used in classrooms. These results may indicate a general reduction of laboratory effects in classrooms, as well as the possibility that other tutoring features of intelligent tutoring systems operate to reduce cognitive load.

Visual-Verbal Knowledge Integration in Geometry

Our goal was to evaluate the impact of integrated learning materials on students' domain understanding following practice in authentic classroom settings. We chose geometry as our domain of study for two reasons.

First, geometry makes heavy use of both visual and verbal information for successful learning. In geometry, visual information consists of a problem diagram and verbal information consists of given text and conceptual, propositional representations of geometry knowledge. Visual information in a geometry diagram provides an explicit representation of information that remains implicit in verbal descriptions (Larkin & Simon, 1987).

Second, there is evidence that integrated visual-verbal representations in geometry support successful problem solving. Previous research has found that experts use key diagram configurations to cue relevant geometry knowledge, and that these diagram configurations can be used to successfully model expert problem solving (Koedinger & Anderson, 1990). Without coordination between visual representations and deep conceptual knowledge, visual cues from geometry diagrams can be unhelpful or even misleading. Visual features from geometry diagrams hurt performance when novices focus on visual similarities in diagrams at the expense of meaningful, logical differences in problems (Lovett & Anderson, 1994).

We chose to study the potential educational impact of integrated materials using a rigorous test case: we embedded the integrated representations in an instructional treatment that has been shown to improve student performance beyond typical classroom instruction and that already includes some mechanisms to reduce cognitive load during student problem solving: the Geometry Cognitive Tutor (described below). Identifying an impact of integrated representations beyond the learning achieved with the standard tutor would suggest that these representations have critical and powerful effects on learning in geometry.

Study 1

Method

Participants Sixty-four students from three 10th grade geometry classes in a rural Pennsylvania school participated in the study as part of their normal classroom activities. Data from 21 students were excluded due to absences during one or more study activities (pretest, posttest, or computer tutoring), leaving 43 students for final analyses.

The Geometry Cognitive Tutor The Geometry Cognitive Tutor is one of several existing Cognitive Tutors. Cognitive tutors are a type of intelligent tutoring system based in the ACT-R theory of cognition and learning (Anderson & Lebière, 1998) and have been described extensively in other publications (e.g., Alevan & Koedinger, 2002; Anderson, Corbett, Koedinger, & Pelletier, 1995). The Geometry Cognitive Tutor supports students' learning by doing; it selects problems during practice, provides feedback on

student responses, provides hints, and tracks students' skill development during learning. For our purposes, we did not change the underlying mechanisms of intelligent tutoring used by the tutor but manipulated the format of visual-verbal representations presented to the students by the tutor.

The Geometry Cognitive Tutor has been shown to significantly improve students' learning outcomes (Alevan & Koedinger, 2002; Anderson et al., 1995), but the standard form of the geometry tutor reflects a split-source presentation (see Figure 1). Despite its split-source format, the existing tutor includes several mechanisms that reduce cognitive load demands on students: the tutor supports a step-by-step problem-solving sequence where the steps are laid out in advance and feedback is given at every step. We compared this existing, split-source tutor to an integrated tutor that we developed for this experimental work.

Split-Source (Table-based) Tutor Format In the standard version of the Geometry Cognitive Tutor, all interactions take place in a table that is spatially separate from the relevant geometry diagram (see Figure 1). Students enter their solutions in the table and the tutor's feedback is displayed in the table. In addition to the numerical values for geometric quantities (such as angle measures), students must name a geometry rule that justifies each step.

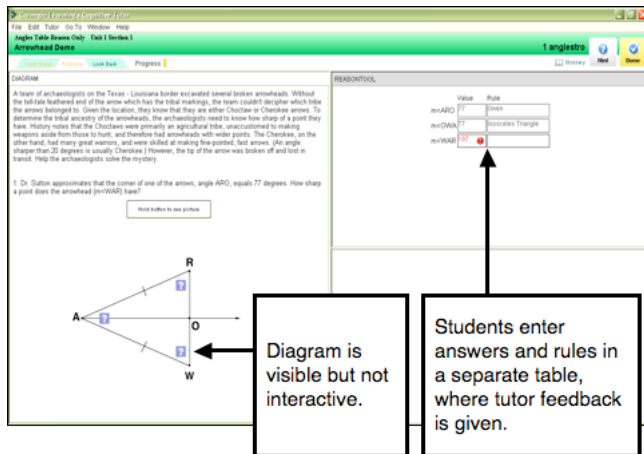


Figure 1: The standard form of the Geometry Cognitive Tutor. Students work in a split-source format.

Integrated (Diagram-based) Tutor Format We developed and implemented an integrated version of the Geometry Cognitive Tutor (see Figure 2). In this tutor, integration is supported in three ways: 1) Integrated Activity: Students interact directly with the diagram representation by clicking on the question-mark icon associated with the problem step (i.e., geometric quantity) they want to solve; 2) Reduced Mapping: Clicking a question mark opens a work area near the diagram that allows students to enter answers and receive feedback without extensive mapping to a distal location; and 3) Integrated Representation: Accepted numerical answers appear in the appropriate location in the diagram (i.e., they replace the corresponding question-mark

icon). A paper version of this integrated representation has been used successfully in lab settings to reduce split attention (Tarmizi & Sweller, 1988). With the exception of these integrated features, the integrated (diagram-based) version of the Geometry Cognitive Tutor performs exactly as the split-source (table-based) version. Problem content, feedback criteria and content, hint availability and content, and the set of solutions recognized as correct were kept constant in each version of the tutor.

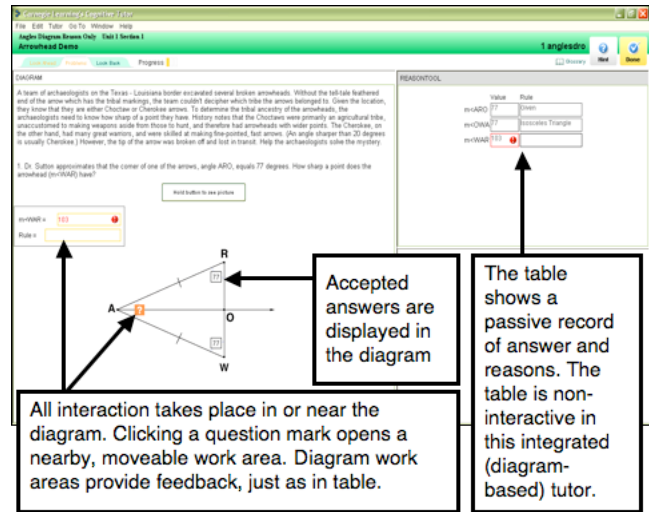


Figure 2: The integrated form of the Geometry Cognitive Tutor. Students interact with and see answers displayed within the geometry diagram.

Pre- and Posttest. The pretest and posttest in this study were given four weeks apart and were identical, except that four versions of the tests were used that differed only in problem order. Tests included eight geometry problems, with multiple problem-solving items in each problem; items covered common geometry principles taught in the Angles unit of the Geometry Cognitive tutor. The pre- and posttest included both solvable and unsolvable items. Solvable items tested problem-solving performance on skills that had been practiced using the tutor (i.e., numerical answers and geometry rules were requested for each problem-solving step). However, deep understanding entails not only application of knowledge, but recognition of situations in which learned skills or procedures are not applicable (Bransford & Schwartz, 1999). Thus, we included far transfer items in the form of unsolvable problems where students needed to recognize that there was not enough information to apply a known geometry rule. For these items, students simply needed to state that the problem was unsolvable to receive credit.

Procedure The pretest was given approximately one week before the students began the Angles unit in the Geometry Cognitive Tutor. At pre- and posttest, students were given 30 minutes to complete the problems. Within each participating classroom, grade-matched pairs of students

were randomly assigned to the split-source (table-based) or the integrated (diagram-based) tutor versions. Students worked on the Angles unit using their assigned tutor version, as part of their regular geometry instruction, during 3 computer lab sessions over a 3-week period (for a total of approximately 3.5 hours). Posttests were given during the first computer session following the study completion, about one week after students last used the tutor.

Study 1: Results and Discussion

A multivariate repeated measures analysis of variance was conducted. The between-subjects factor was tutor version (split-source vs. integrated) and the within-subjects factor was test time (pretest vs. posttest); dependent measures were performance on problem-solving items, for both numerical answers and geometry rules, and far transfer items that required identification of unsolvable problems.

All participants showed a significant improvement from pre- to posttest ($F_{(3, 39)} = 32.5, p < .001$), but there were no significant differences in student performance on the dependent measures (see Table 1).

Table 1: Study 1 Posttest means and (*standard deviations*) for percent correct on practiced and transfer skills.

Test Item	Split-Source	Integrated
Numerical Ans.	54 (31)	46 (27)
Geometry Rules	46 (29)	45 (27)
Unsolvable Prob.	24 (32)	28 (33)

These results may not be entirely unexpected given potential difficulty of replicating significant materials effects from laboratory settings in classroom environments (cf., Olina et al., 2006). Indeed, significant learning from pre- to posttest demonstrated that classroom use of both versions of the tutor were effective for at least some forms of procedural and declarative knowledge.

However, we were concerned that the relatively coarse far transfer task (the identification of unsolvable problems) may not have been sensitive to potential differences in knowledge representation that could be supported by integrated materials during classroom practice. That is, students could draw upon a deep, integrated visual-verbal knowledge in analyzing given information, diagram features, and known geometry rules to conclude that a problem was unsolvable. However, students could have based solvability judgments simply on perceived difficulty of a problem, failure of an existing procedural solution, or lack of recognition for the problem situation from practice.

Study 2

To more thoroughly test for students' integrated knowledge development when using the integrated version of the Geometry Cognitive Tutor, we conducted a second study later in the school year using more sensitive testing materials that included expanded far transfer items in a larger sample of classrooms.

Method

The tutor versions used in Study 2 were identical to Study 1, with the exception that the Circles unit of the Geometry Cognitive Tutor was used since participating classrooms had completed the Angles unit earlier in the school year. As described below, the study included an expanded pre- and posttest. An identical procedure was used in both studies.

Participants One hundred thirty-six students from eight new 10th grade geometry classes in the same rural Pennsylvania school participated in the study during as part of their normal classroom activities. Data from 45 students were excluded due to absence during one or more of the study activities (pretest, posttest, or computerized tutoring sessions), leaving 91 students in the final analyses.

Expanded Pre- and Posttest Pre- and posttests in this study included six types of items in three categories. First, problem-solving items were used as in Study 1. Problem-solving included: 1) numerical answers, and 2) geometry rules used to justify numerical answers.

Second, far transfer items in the form of unsolvable problems were included as in Study 1, but these items were expanded to require explanations of the unsolvable problems in addition to simple identification. Students had to name a geometry rule that *could* be used to solve the problem if additional information was known about the problem diagram (e.g., the chord product rule could be used if you knew the measure of chord AC).

Third, True/False items were developed that needed no numerical problem solving, but instead required students to reason about the applicability of geometry rules to elements in a given geometry diagram. For example:

“You can use the **exterior angle** rule to find angle STF if you know only the measures of arc CBF and arc DE.”

Students identified each statement as true or false; for false answers, students were required to state what diagram features would need to be known in order to use the stated rule to find the goal feature. Valid explanations were required to receive full credit for false answers; false answers without valid explanations received half credit.

Explanations for both the unsolvable problems and the false answers required students to draw upon knowledge of conceptual geometry rules in the context of a visual diagram representation. Neither skill had been practiced explicitly in either tutor version, these items tested far transfer and deep understanding of visual-verbal knowledge in geometry.

Study 2: Results and Discussion

A multivariate repeated measures analysis of variance was conducted. The between subjects factor was tutor version (split-source vs. integrated) and the within subjects factor was test time (pretest vs. posttest). Dependent measures included performance on numerical answers and geometry rules, identification and explanation of unsolvable problems, and performance on true and false items.

Table 2: Study 2 Posttest means and (*standard deviations*) for percent correct on practiced and transfer skills

Test Item	Split-Source	Integrated
Numerical Ans.	30 (25)	37 (26)
Geometry Rules	20 (21)	25 (25)
Unsolv. Prob. Identify	24 (26)	27 (32)
Unsolv. Prob. Explain	06 (11)	13 (19)
True Items	72 (22)	71 (25)
False (+Explain) Items	17 (13)	23 (17)

As in Study 1, all participants' scores improved significantly from pre- to posttest ($F_{(6, 84)} = 9.1, p < .001$). However, condition differences depended upon the type of knowledge being tested. No condition effects or interactions were found for skills practiced in the tutor (see numerical answers and geometry rules, in Table 2).

Analyses of the varied far transfer items show an advantage for students using the integrated tutor, especially for student performance on true/false items. As noted earlier, these items required students to reason about geometry rules in the context of a visual diagram. True answers required recognition of valid applications of rules; false answers required students to recognize inappropriate applications and to reason about how geometry rules could correctly apply to a diagram. Results show no interaction between test time and condition for true items – students are equally able to recognize a correct application of a geometry rule. However, a significant test time by condition effect ($F_{(1, 89)} = 4.3, p = .04$) was found for false items. As seen in Figure 3, students in the integrated condition performed best at identifying and explaining false items at posttest.

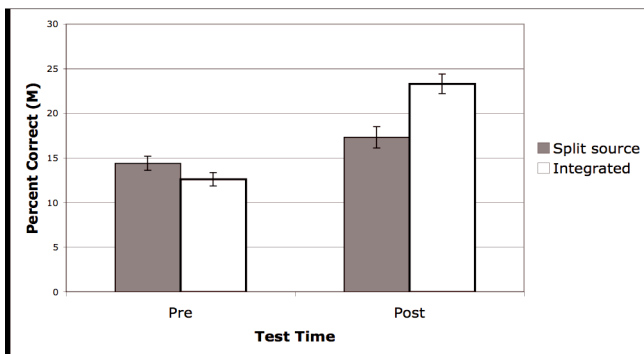


Figure 3: Mean (+ SE) performance on identification and explanation of false items: Test time by condition.

Student performance on the more difficult far transfer items – identifying and explaining unsolvable problems – showed a similar advantage for students using the diagram-based tutor. However, this advantage was found solely for the combined reasoning with visual and conceptual information. Simple identification of unsolvable problems was consistent with Study 1: neither a significant condition difference nor a test time by condition interaction was found

(see Table 2). However, student explanations showed a potential, though only marginally significant, interaction of test time and condition ($F_{(1, 89)} = 3.4, p < .07$) in the predicted direction. At posttest, students in the integrated condition were better able to explain how to make unsolvable problems solvable (see Figure 4).

It should be noted these far transfer items are quite difficult since they require analysis of relationships among diagram features as well as connections to known geometry rules. It is not terribly surprising that overall performance levels of performance are low, but it is noteworthy that students using the integrated materials perform about twice as well as students using the split-source tutor version.

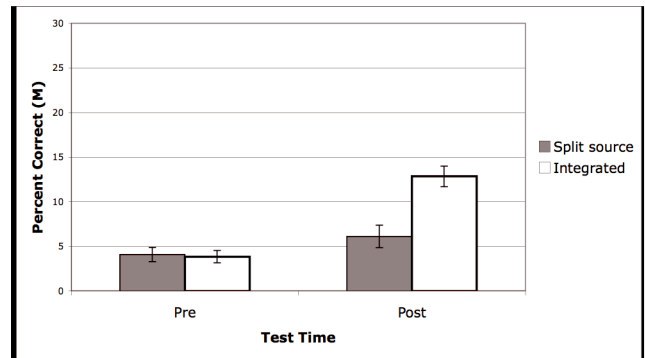


Figure 4: Mean (+ SE) performance on explanation of unsolvable problems: Test time by condition.

General Discussion

These studies suggest that integrated representations can have impact on student learning, especially when assessments include measures of far transfer that assess connections between conceptual knowledge and visual representations. Our results demonstrate that students who used the integrated (diagram-based) version of an intelligent tutor were better able to explain how inappropriate applications of geometry rules to diagram features could be resolved when compared to students who used a split-source (table-based) version of the tutor. Student using the integrated version of the tutor also tended to better explain how to make unsolvable problems solvable. It is notable that an effect of integrated representations occurred even though all learners significantly improved their knowledge from pre- to posttest following tutor practice in class. Our results provide preliminary evidence that integrated representations can influence students' development of deep connections between visual and verbal knowledge in geometry.

The lack of condition differences in the first study suggests the need for careful, sensitive assessment tasks that specifically target applications of visual and verbal knowledge. Although the effects in Study 2 replicate the assessment results from Study 1, more sensitive far transfer tasks indicate that integrated representations can have potentially important effects on student learning.

It should be noted that the diagram-based interface that we developed supported visual-verbal integration in more

than one way. Students interacted directly with the diagrams, they worked nearer the relevant diagrams when entering answers and receiving feedback, and correct answers appeared in the diagrams. It may be the case that these different aspects of integration are differentially effective in supporting deep understanding. It is also possible that overall integration may be less important than support in mapping between representations (i.e., the split-source condition may benefit from implementing linked representations where accepted answers appear in the diagram). The current studies cannot discriminate between these possibilities. Further research is needed to understand what aspects of integrated learning materials promote optimal learning and how they may be tied to integrative cognitive processes. Using think-aloud protocols, we currently are exploring how the integrated tutor may support key learning processes during practice.

Overall, we need to know more about the integration processes that operate when learning with visual and verbal information. Future work should continue to explore how to support these processes using educational technology and intelligent tutors in authentic classroom settings.

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