Integrating Visual and Verbal Knowledge During Classroom Learning with Computer Tutors

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Abstract

Prior research in multimedia learning has demonstrated that representations that present visual and verbal information in an integrated, rather than split-source, format can support successful learning outcomes. These benefits are often attributed to reductions in cognitive load during learning; however, it may also be the case that these materials support cognitive integration processes that connect visual and verbal knowledge representations. Effects on cognitive integration processes should promote benefits for deep understanding that persist with extended practice in real classrooms. 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 deep transfer tasks that hinged on an understanding of the connections between conceptual geometry principles and diagram features. These findings suggest that integrated representations support students' developing visual-verbal knowledge representations during learning.

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

Introduction

Previous work in multimedia learning has shown that the format in which visual-verbal information is presented can influence student performance (Butcher, 2006; Hegarty & Just, 1993; Kalyuga, Ayres, Chandler, & Sweller, 2003; Kalyuga, Chandler, & Sweller, 2000; Mayer, 2001; Moreno & Mayer, 1999). Some research has specifically compared the impact of split source vs. integrated materials, where "split source" refers to materials that do not link or connect visual and verbal information during learning and "integrated" refers to materials that closely coordinate visual and verbal information. This 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 in an intelligent geometry tutoring system on students' problem solving and deep transfer, when students use the integrated materials during extended practice in real classrooms. In this paper, we present the results of two studies that compare the effects of an (experimenter-designed) integrated version of the Geometry Cognitive Tutor to a standard, split-source version of the tutor. We hypothesized that integrated materials that support students' reasoning with visual and verbal information during practice would support the development of integrated visual-verbal knowledge representations, resulting in deep learning and transfer.

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 information at the same time leads to better learning than presenting them at different times (Mayer & Anderson, 1992; Mayer, Moreno, Boire, & Vagge, 1999). Research also has identified the importance of 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; Mayer, 1989; Moreno & Mayer, 1999). One proposed theoretical rationale for these "contiguity effects" is that temporal and spatial coordination reduces the 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 materials depicting close connections between visual and verbal representations may spur cognitive processing that integrates visual and verbal information into existing knowledge representations. That is, representations that prompt the learner to consider and process connections between visual and verbal information may support the development of integrated visual-verbal knowledge representations. Generally, we assume that these integration processes are cognitive processes that operate between internal visual and verbal knowledge representations (Schnotz & Bannert, 2003).

There is some evidence that supporting the active integration 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 representation using initially split-source materials (Bodemer, Ploetzner, Feuerlein, & Spada, 2004). Other research has shown that mental model development can be supported by diagrams that prompt learners to generate integration inferences during learning (Butcher, 2006). We interpret these results as evidence that learning can be supported by presenting students with materials that promote integration processes, especially when the materials include both visual and verbal sources of information.

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). Specifically, a cognitive load approach would suggest that integrated materials reduce the effort needed to map between visual and verbal information, allowing cognitive effort to be focused on deeper processing during learning.

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 knowledge reduces cognitive load effects during learning (e.g., Kalyuga et al., 2003; Kalyuga et al., 2000). Kalyuga et al. (2003) have termed this interaction between learner knowledge and cognitive load influence the 'expertise reversal effect'. Thus, the impact of materials that reduce cognitive load demands on learners fades with time as learners develop increasing skills and expertise.

Although it may not be the case that classroom learners develop the level of knowledge at which expertise reversal becomes important, 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 study and practice in classroom settings. Other studies (e.g., McLaren, Lim, Gagnon, Yaron, & Koedinger, 2006) also have found that laboratory-identified effects do not affect student performance when interventions are used in classrooms or intelligent tutoring systems. These results may indicate a general effect of classrooms that changes the effects of laboratory manipulations or the possibility that other tutoring features 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 extended 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 may 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 in geometry (Koedinger & Anderson, 1990). Without such integrated visual-verbal knowledge representations, visual cues from geometry diagrams can be unhelpful or even misleading. Visual features from geometry diagrams can hurt performance when novices focus on visual similarities in geometry 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 proven to improve upon 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 can have critical and powerful effects on learning in geometry.

Study 1

Method

Participants Sixty-four students from three 10^{th} grade geometry glasses 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., Aleven & 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 visual-verbal representations presented to the students by the tutor.

The Geometry Cognitive Tutor has been shown to significantly improve students' learning outcomes (Aleven & Koedinger, 2002; Anderson et al., 1995; Koedinger, Anderson, Hadley, & Mark, 1997), but the standard form of the geometry tutor reflects a split-source presentation. Despite its split-source format, the existing tutor includes 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 the 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; the tutor's feedback is also 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.

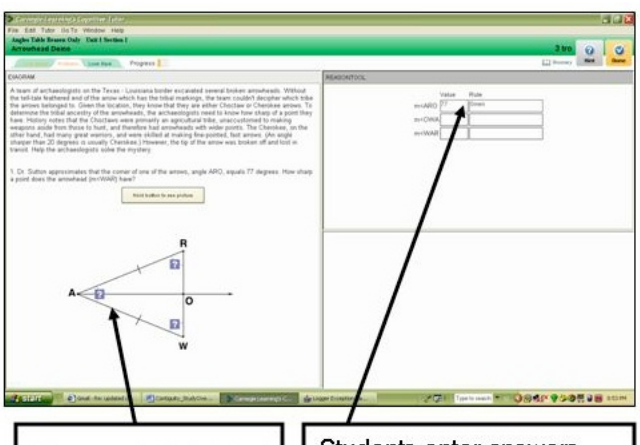

Figure 1: The standard form of the Geometry Cognitive Tutor. Students work in a split-source format.

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 during learning by clicking on the question-mark icon associated with the problem step (i.e., geometric quantity) they want to solve next; 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 diagram, in the appropriate location (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 during geometry learning (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.

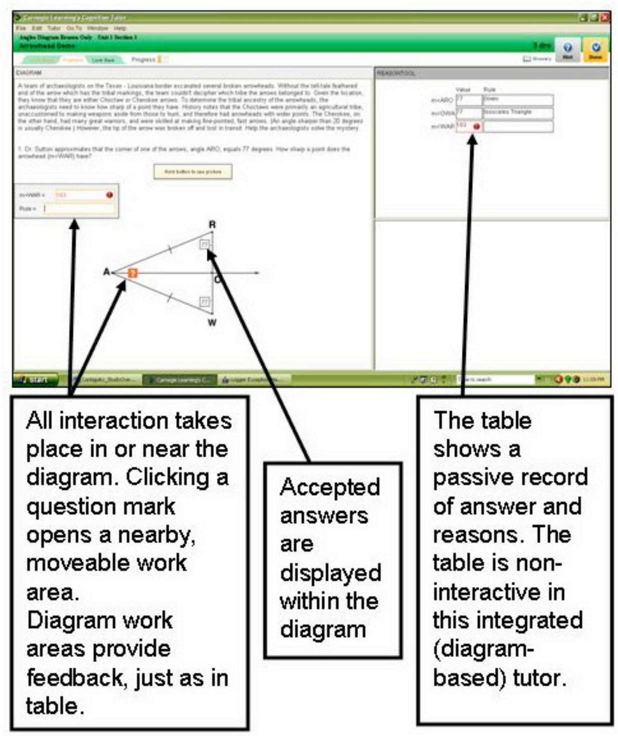

Figure 2: The integrated form of the Geometry Cognitive Tutor. Students interact with and see answers displayed within the geometry diagram.

Pre- and Posttest. The pretest and posttest in this study were identical, except that four versions of the tests were used that differed only in problem order presented to students. The test included eight geometry problems, with multiple problem-solving items in each problem, that 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 as practiced in the tutor (i.e., numerical answers and geometry rules were requested for each problem-solving step). Unsolvable items served as transfer items; students simply needed to state that the problem was unsolvable to receive credit for these items.

Procedure 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 of the Geometry Cognitive Tutor using their assigned version of the Geometry Cognitive Tutor, 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).

The pretest was given approximately one week before the students began the Angles unit in the Geometry Cognitive Tutor. Posttests were given in the first class period following the study completion. At pre- and posttest, students were given 30 minutes to complete the problems.

Study 1: Results and Discussion

A repeated measures multiple 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, geometry rules, and identification of unsolvable problems.

Although all participants showed an overall significant improvement from pre- to posttest ($F_{(3, 39)} = 32.5$, $p < .001$), there were no significant condition differences nor test time by condition interactions for performance on numerical answers, geometry rules, or identification of unsolvable problems.

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 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 extended practice. That is, students could draw upon a deep, integrated representation to analyze given information, diagram features, and known geometry rules to conclude that a problem was unsolvable. However, students also could have based solvability judgments simply on the perceived difficulty of a problem, the failure of an existing procedural solution, or a lack of recognition for the problem situation from practice.

To more thoroughly test for integrated knowledge development, we conducted a second study using more sensitive testing materials with a larger sample of participants to further explore the effects of integrated materials during geometry learning.

Study 2

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 as the topic of practice and assessment. As described below, the study included a larger sample of participants and an expanded pre- and posttest. An identical procedure was used in both studies.

Participants One hundred thirty-six students from eight new 10^{th} grade geometry glasses 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 The pre- and posttest in this study included six types of items in three general categories. First, standard items tested students' problem-solving abilities as in Study 1. Two dependent measures were included in these items: 1) numerical answers, and 2) geometry rules used to justify numerical answers.

Second, 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. Explanations required students to indicate how the problem could be made solvable. Students had to name a geometry rule that *could* be used to solve the problem if additional information was known about the problem diagram.

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 element. 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. Thus, these items represented deep-transfer items that tested the degree to which students had developed the integrated visual-verbal knowledge necessary to troubleshoot diagram applications of geometry rules.

Study 2: Results and Discussion

A repeated measures multiple 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 geometry statements.

Overall, all participants' scores improved significantly from pre- to posttest ($F_{(6, 84)} = 9.1$, $p < .001$); thus, both versions of the geometry tutor supported significant learning during the study period. However, condition differences depended upon the type of knowledge being tested. No condition effects nor interactions were found for skills practiced with the tutor (see Answers and Rules in Table 1).

Table 1: Study 2 Posttest means and (*standard deviations)* for percent correct on practiced and transfer skills

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

Analyses of the varied transfer items show an interesting pattern. Student performance on identification of unsolvable problems was consistent with Study 1: there was not a significant condition difference nor was there a test time by condition interaction. Students using the split-source and the integrated versions of the Geometry Cognitive Tutor performed equally well when identifying unsolvable problems (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 3).

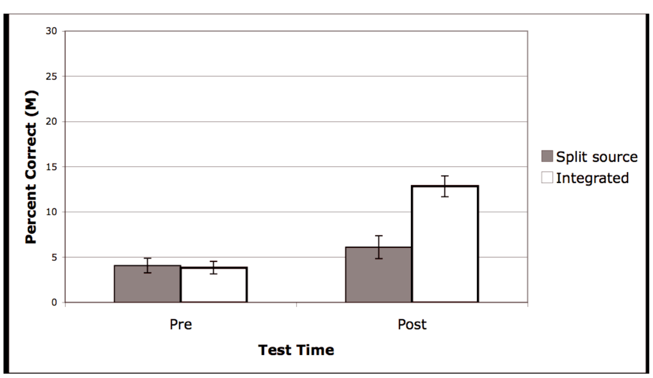

Figure 3: Mean (+ SE) performance on explanation of unsolvable problems: Test time by condition.

A similar transfer effect can be seen for students' performance on true/false items. As noted earlier, these items required students to reason about geometry rules in the context of a problem diagram. True answers required students to recognize valid applications of rules, false answers required students to recognize inappropriate applications and to explain how stated rules could be correctly applied to the diagram. There was no interaction between test time and condition for true items. However, a significant test time by condition effect ($F_{(1, 89)} = 4.3$, $p = .04$) was found for performance on false items. As seen in Figure 4, students in the integrated condition performed best at identifying and explaining false items at posttest.

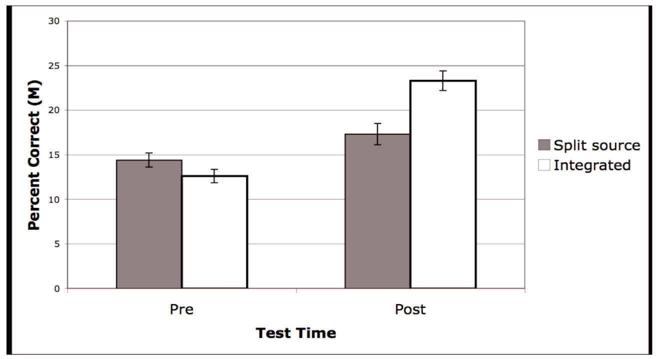

Figure 4: Mean (+ SE) performance on identification and explanation of false items: Test time by condition.

General Discussion

These studies suggest that integrated representations can have impact on student learning, especially when assessments include measures of deep transfer. Our assessments show 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 noteworthy that an effect of integrated representations occurred even though all learners significantly improved their knowledge from pre- to posttest following tutor practice in class. These results represent 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 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 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 accepted 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 integration may be less important than mapping support 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.

Acknowledgments

The authors thank Octav Popescu, Andy Tzou, Carl Angiolillo, Thomas Bolster, and Grace Leonard for their contributions. Special thanks to Colleen Conko, Terri Murphy, Sabine Lynn, and Dan Lusk for their dedication to and help with these studies. This work is supported by the Pittsburgh Science of Learning Center through funding from the National Science Foundation (# SBE-0354420). The opinions and conclusions presented here are those of the authors and do not necessarily reflect the funding agency.

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