Reciprocal Relations Between Research and Practice: How Improving Curricular Materials Led to New Research Questions

To improve classroom outcomes, the relationship between research and practice needs to be iterative and bi-directional. The National Center for Cognition and Mathematics Instruction aims to apply cognitive-based design principles to revise a middle school mathematics curriculum and to evaluate the effects of the revised materials on student outcomes. Investigators will report on the reciprocal relations between research and practice. Though the primary goal of the Center is to apply research to practice, the act of revising existing materials has led to additional research questions that have both theoretical and practical implications. Presenters will discuss research findings based on the integration of research-based design principles with existing instructional materials and will outline new research questions that emerged from these efforts.

Objectives

Do research findings from laboratory-based studies in cognitive and learning sciences generalize to real classrooms? How does the application of theory to practice lead to new research questions? The National Center for Cognition and Mathematics Instruction (Math Center) was formed to integrate research and practice by bringing together experts in cognition, instruction, assessment, research design, measurement, mathematics education, and teacher professional development. The Math Center goals are to apply cognitive-based design principles to revise a middle school mathematics curriculum and to evaluate the effects of the revised materials on student outcomes. The work of the Math Center focuses on four cognitive principles from the Institute for Education Sciences *Practice Guide* (Pashler, 2007). These principles include (1) combining visual with verbal information to promote the integration of concepts, (2) structuring practice by interleaving worked examples and self-explanation prompts with new problems to solve, (3) carefully spacing the learning of critical content and skills over time, and (4) using focused feedback on quizzes and homework to promote student learning.

In this session, investigators will report on the reciprocal relations between research and practice. Though the primary goal of the Center is to apply research to practice, the act of revising existing materials has led to additional research questions that have both theoretical and practical implications. Presenters will discuss research findings based on the integration of research-based design principles with existing instructional materials and will outline new research questions that emerged from these efforts.

Overview

The first of four presenters will introduce the efforts to redesign the Connected Mathematics Project (CMP) middle school mathematics curriculum using design principles from cognitive research. The process for integrating research into practice and present findings from a randomized control trial designed to measure the efficacy of the revised instructional materials will be discussed. The remaining three presenters will outline the cognitive design principles and discuss the reciprocal relationship between research and practice. Each presenter will describe findings related to new research questions that emerged from the design phase of the curricular revision processes. Finally, Dr. Elizabeth Albro, Associate Commissioner for Teaching and Learning

Teaching and Learning Division-National Center for Educational Research, will serve as discussant. Dr. Albro will address general issues related to integrating research findings into authentic classroom contexts.

Significance

To improve classroom outcomes, the relationship between research and practice needs to be iterative and bi-directional. Currently, there is a shortage of research on the integration of empirical findings with instructional practice. In the symposium, presenters will discuss how improving curricular materials led to new research questions.

Structure of the session

The group session will be a Symposium and allow for a mix of focused presentations on the specific scholarly work and broad-based discussions. The four presentations will be allocated half of the total session time (45 minutes). The discussant will have 15 minutes to make general comments and address the two framing questions. The remaining time will be spent in moderated discussion with audience participants.

Implementing and Evaluating the Efficacy of Applying Research to Practice in Middle School Mathematics

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Research in cognitive and learning sciences has led to a number of recommendations for improving learning and instruction (Pashler et al., 2007). Despite advances in our understanding of student learning in multiple subject areas, research often fails to inform the design of instructional materials and practices. Applying research to practice requires new processes for curricular design that involve multidisciplinary teams including cognitive researchers, instructional designers, mathematics content experts, and professional development providers. In this presentation, we will share our methodology for integrating research-based design principles with the existing Connected Mathematics Project 2 (CMP2) curriculum and report results from a randomized control trial.

To test whether research can be effectively translated into practice, the Connected Mathematics Project 2 (CMP2) curriculum was revised according to four principles; 1) verbal-visual mapping, 2) interleaving worked examples, 3) spacing learning over time, and 4) using formative assessment. One hundred and nine 6^{th} and 8^{th} grade teachers, experienced with the CMP2 curriculum, participated in our study. Teachers represented a wide diversity of schools across seventeen states. Our study used a within-teacher design. All study teachers provided data from one revised unit and one control unit. Whether a given unit was used in its original or redesigned format was counterbalanced across participants.

Participating teachers attended a two-day, online, professional development workshop to introduce them to the research-based principles and implications for instructional materials and practice. During these interactive sessions, teachers worked as a group and in pairs to plan instruction for the treatment units. Further, teachers were made aware of study requirements including the administration of pre- and posttests and completion of weekly instructional logs.

To evaluate student learning, we created assessments that included researcher-created items as well as items from standardized tests such as NAEP, TIMSS, and the California Standards Test in mathematics. Students completed a pretest before and posttest after each of the two units (treatment and control). To test whether the revised units promoted greater student learning than the existing units, we fit conditional, mixed effects multilevel models (e.g., Goldstein, 1987; Raudenbush & Bryk, 2002; Murray, 1998). The random effect of teacher is included in the model to account for within-site clustering. Potential fixed effects include treatment group, baseline (pre-test) measures of student outcome variables, and other observed covariates measured prior to random assignment.

Our research outcomes include both new processes for integrating research and practice as well as findings that reveal the extent to which the principled redesign of curricular materials influences student learning. Our iterative, multi-layered design process, that we developed for integrating the cognitive principles with an existing curriculum could be readily applied across subject areas, and our empirical findings, will provide evidence of the outcomes of applying research to practice in authentic classroom settings.

Worked Examples: Who do they Work for?

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This presentation will describe work done by the Worked Examples team of the NCCMI to adapt the Connected Math curriculum to include worked examples and prompts for self-explanation in the ACE problem sets at the end of each investigation. An abundance of laboratory work (e.g., Sweller & Cooper, 1985) has demonstrated that replacing approximately half of the problems in a problem set with worked examples leads to improved student learning; this study aims to corroborate this claim in real-world classroom settings.

Prompting students to explain worked examples is thought to improve learning because explanation helps students to integrate new information with their prior knowledge and forces them to make newly-acquired knowledge explicit (Chi, 2000; Roy & Chi, 2005). This combination is typically implemented by replacing a problem with an example of how to solve the problem correctly and asking students to explain why the solution is correct. However, variants on this approach have also been shown to enhance learning. For instance, a growing body of literature suggests that explaining a combination of correct and incorrect examples (i.e., explaining why an incorrect procedure is wrong) can be more beneficial than explaining correct examples alone (e.g., Siegler & Chen, 2008). Further, there is support for providing students with partially worked examples as they become more proficient with problem-solving; in these faded examples, part of a problem is worked out for the student and they must then complete the problem (e.g., Renkl, Atkinson, Maier, & Staley, 2002). The present study incorporates a combination of correct and incorrect examples with self-explanation prompts and partial worked examples.

In a series of unit studies, classrooms were randomly assigned to receive the original or adapted version of the ACE problems. Teachers administered pre- and posttest surrounding completion of the unit and were instructed to use the materials as they would normally, thus students completed the ACE problems independently as in-class or homework assignments. Results from these studies will be discussed in terms of the effectiveness of the worked-example/self-explanation technique as part of an established curriculum in real-world classrooms. Despite strong support for this technique in laboratory studies, prior laboratory studies have established that the technique can be more or less effective depending on students' prior knowledge of the content area (e.g., Kalyuga, Chandler, & Sweller, 2001; Grosse & Renkl, 2007). Results from classroom studies reveal that the degree of effectiveness of the materials may also differ based on other student characteristics, such as socio-economic status, ethnicity, prior spatial skills, and understanding of numerical magnitudes. These studies contribute to the ongoing debate about the ease of translating laboratory-proven techniques into real-world instructional settings, and argue for increased study of individual differences in the effectiveness of such techniques.

Applying Principles of "Spacing" and "Testing" to Improve Student Learning of Mathematics

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Our project has focused on addressing complementary curricular redesign and empirical learning questions associated with implementing two research-based principles for improving instruction and student learning. The *IES Practice Guide* (Pashler et al., 2007) provides multiple research-based recommendations for improving instruction, one of which is the spacing of practice over time (e.g., Cepeda et al., 2006). The spacing effect is complementary to a second recommended principle focused on quizzing and assessment (e.g., Butler & Roediger, 2007).

Applying these principles to the redesign of mathematics curricular materials requires that there be a clear and consistent definition of the "what" that is being practiced or assessed and when it is introduced, practiced, and assessed over the three-year span of the curriculum. Our first step was to identify the "what" and then trace occurrences from initial mastery to subsequent opportunities for practice within and across mathematical units in grades 6-8. We have identified over 150 concepts that occur in *Connected Mathematics Project* (*CMP)* and about 70 prerequisite relationships between the concepts, which were then applied to mapping all *CMP* homework and assessment problems in sixth and seventh grade and selected eighth grade units. Through this analysis, we were able to ascertain the practice frequency of specific concepts and identify concepts that were expected to be mastered before the start of a new unit, and which of these already-mastered concepts frequently appeared in the new unit.

Knowing what is being practiced and assessed does not immediately tell us what changes need to be made to optimize student outcomes. Thus, we have pursued empirical studies to assist in structuring the redesign of curricular materials and teacher instructional practice. Two questions of concern were: (1) how well have students retained previously "mastered" mathematical concepts given existing practice regimens, and (2) does additional practice of relevant prior concepts, with reacquisition of mastery if needed, aid in the acquisition of new mathematical content? It was hypothesized that opportunities to practice and re-master relevant prior concepts would better prepare students to learn new mathematical content and, therefore, demonstrate higher levels of proficiency compared to practice and re-mastery of concepts not directly germane to the target unit.

Two weeks prior to the start of a new CMP unit, 151 middle school students received practice—with hints and feedback—on a set of concepts either relevant or irrelevant to the to-be-learned content of the upcoming unit. Both sets of concepts were ostensibly mastered at earlier points in the curriculum. Results indicate that students' retention of previously mastered concepts varies considerably across concepts. Furthermore, as predicted, students who received practice on a set of relevant concepts performed better at the post-test assessing understanding of the new unit content than students who practiced irrelevant concepts. This finding is significant because it suggests that it may be beneficial for students to "re-master" concepts that were ostensibly already mastered, especially if those concepts appear frequently in contexts where new material is practiced and assessed. Incorporating changes based on these results into the curriculum will also be discussed.

The role of contextual illustrations in problem-solving accuracy and lesson-text comprehension

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Mathematics textbooks contain a multitude of visual representations, both relevant and irrelevant to instruction. In the process of modifying the visual representations in Connected Mathematics Program 2 based on cognitive science principles, we have developed new research questions regarding the role of visual representations in mathematics learning. For example, information that is interesting, but irrelevant to the text, can distract learners and diminish comprehension, a phenomenon referred to as the *seductive details effect* (Lehman, Schraw, McCrudden, & Hartley, 2007). Because of this, decorative images have been found to negatively affect learning (Levin, Anglin, & Carney, 1987). But it is uncertain how contextual images, which visually represent the situation verbally described in a story problem or lesson text, affect mathematics learning. Specifically, it is unknown whether contextual images distract from mathematics learning in a manner similar to decorative images or if they benefit mathematics learning through assistance with reading comprehension (e.g., Pike, Barnes, & Barron, 2010). In two experiments presented here, the influence of contextual images on problem solving and lesson text comprehension is examined. Experiment 1 examines the effect of contextual illustrations that match the scenario from the text and are arranged in the spatial layout relevant to a trigonometry problem. Experiment 2 examines the effect of contextual illustrations related to the scenarios described in a text on mathematical functions.

In Experiment 1, undergraduate students (N = 89) solved four trigonometry problems in a 2 (diagram presence) by 2 (contextual-illustration presence) within-subjects design. Participants in all conditions benefited from the presence of the diagram (see Figure 1). However, the effect of illustrations varied among subgroups. The subgroup of mathematics/science majors who received their prior education outside of the United States performed better with the illustration. The subgroup of non-mathematics/science majors who received their prior education in the United States performed worse with the presence of an illustration. Therefore, learner background appears to influence the effects of contextual illustration on problem-solving performance. It may be that contextual images lead either to distraction and/or enhanced comprehension, depending on learner background.

In Experiment 2, undergraduate students (N = 41) read four lessons on functions in a 2 (contextual-illustration presence) by 2 (decorative-image presence) within-subjects design while their eye movements were recorded. There was little visual attention, as indicated by total fixation duration, on either the contextual or decorative images, especially compared to the text (see Tables 2 and 3 and Figure 2). Given the minimal visual attention on the contextual and decorative images, it is not surprising that the presence of such images did not influence learning from the lessons (see Figures 3 and 4).

The findings from the two experiments indicate that learners actively engage with visual representations during problem solving, but may ignore them while reading. A follow-up experiment will use questioning to prompt learners to attend to visual representations while reading. It is hoped that questioning will encourage learners to integrate the text and visual representations while reading in a manner similar to problem solving.

References

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Levin, J.R., Anglin, G.J., & Carney, R.N. (1987). On empirically validating functions of pictures in prose. In D.M. Willows & H. Houghton (Eds.), *The psychology of illustration: Volume 1. Basic research* (pp. 51-86). New York: Springer-Verlag.

Pike, M.M., Barnes, M.A., & Barron, R.W. (2010). The role of illustrations in children's inferential comprehension. *Journal of Experimental Child Psychology, 105*, 243-255.

Figure 1

Average Accuracy (+/- SE)

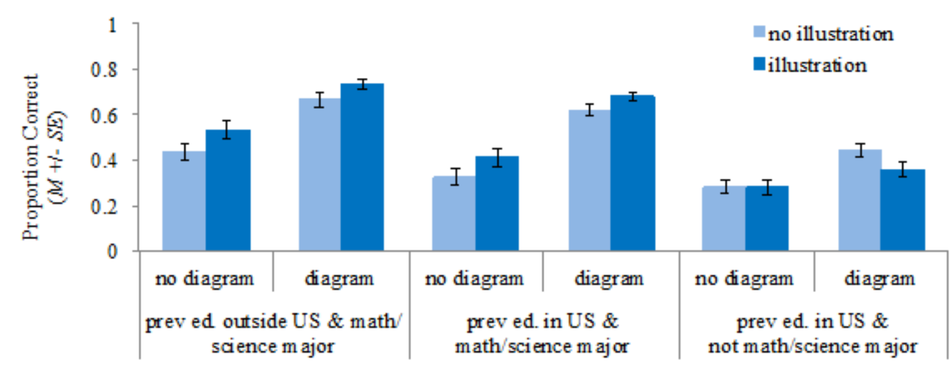


Table 2

Means and standard deviations of total fixation durations (in seconds) for mathematically irrelevant information by visual representation condition

	Contextual Image M(SD)	Decorative Image M(SD)
Both	.97(1.12)	.31(.38)
Context	.72(1.11)	-
Decorative	-	.88(1.02)
None	-	-
Total	.83(1.15)	.55(.82)

Note: N = 41. Both = contextual illustration and decorative illustration, Context = contextual illustration, Decorative = decorative illustration, and None = no illustrations,.

Table 3

Means and standard deviations of total fixation durations (in seconds) for mathematically relevant information by visual representation condition

	Introduction M(SD)	Problem M(SD)	Graph M(SD)	Closing M(SD)
Both	13.51(15.09)	14.86(21.19)	3.35(5.06)	14.79(13.36)
Context	13.13(14.50)	17.30(19.19)	3.39(5.39)	11.76(7.60)
Decorative	14.10(15.60)	19.73(21.97)	3.19(7.73)	14.00(10.42)
None	15.75(17.10)	17.76(16.63)	3.88(5.73)	14.58(8.99)
Total	14.17(15.53)	17.56(19.60)	3.46(6.05)	13.78(10.11)

Note: N = 41. Both = contextual illustration and decorative illustration, Context = contextual illustration, Decorative = decorative illustration, and None = no illustrations.

Figure 2

Heatmap of fixations from a participant in Experiment 2 for a lesson text with contextual and decorative images

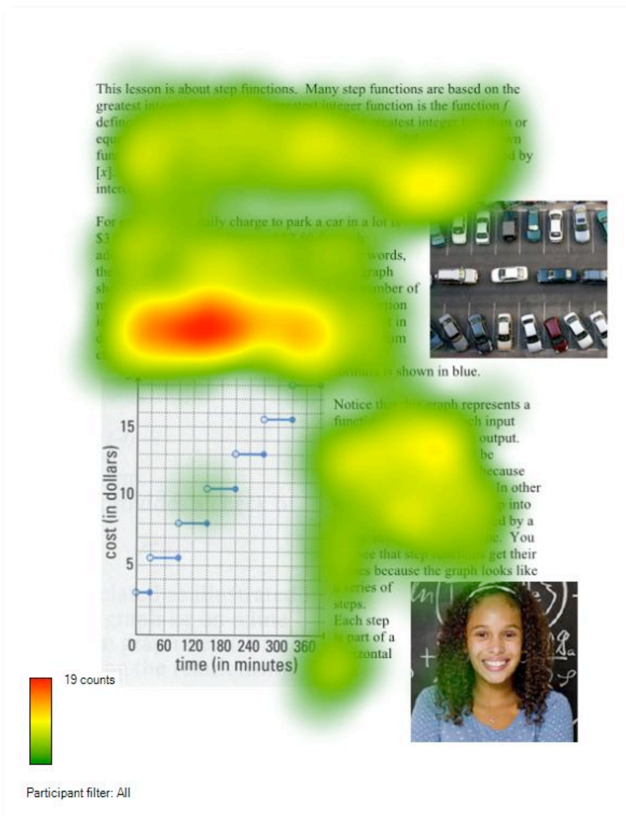
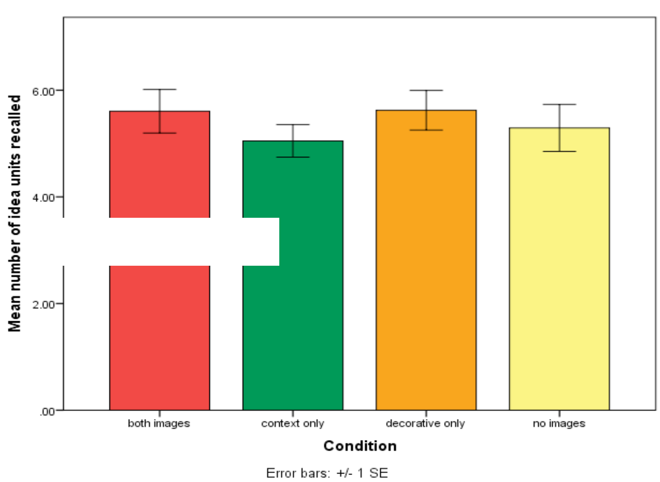


Figure 3

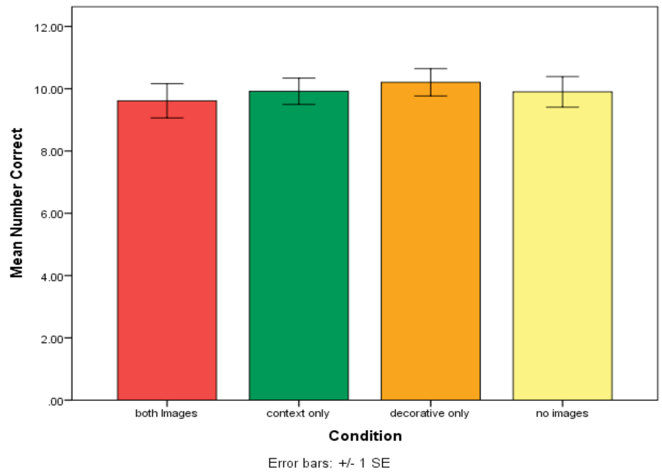
Means of idea units recalled and scores for answers to test questions by visual representation condition



Note: N = 41. Both = contextual illustration and decorative illustration, Context = contextual illustration, Decorative = decorative illustration, and None = no illustrations.

Figure 4

Means of scores to answers to test questions by visual representation condition



Note: N = 41. Both = contextual illustration and decorative illustration, Context = contextual illustration, Decorative = decorative illustration, and None = no illustrations.