Conceptualizing Teacher's Practices in Supporting Students' Mathematical Learning in Computer-Directed Learning Environments

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Abstract: In this paper, we suggest a different conceptualization of teachers' practices in supporting students' mathematical learning in a cognitive tutor or computer-directed learning environment. The CT program examined in this study aimed to enhance students' learning of proportional reasoning through an engaging engineering/robotics context. Students of teachers who assumed an active role in engaging students in mathematical conversations away from the cognitive tutor exhibited significant learning gains, whereas students in settings using the cognitive tutor as designed (with limited interaction from the teacher) did not exhibit learning gains. This research has implications for reconsidering the teacher's role in cognitive tutor or computer-directed learning environments.

Purpose and Framework

Cognitive tutors are a specific type of intelligent tutoring system (ITS) that use technologies associated with curriculum sequencing, intelligent solutions analysis and/or problem solving support to assist students' learning (Brusilovsky & Peylo, 2003). Research on the impact of cognitive tutors (CT) on students' learning of mathematics often assumes a teacher-less environment, with the CT directing the teaching and learning of specific production rules associated with students' ability to correctly complete mathematics problems (Koedinger & Corbett, 2006; Anderson, et.al, 1995). Because teaching and learning are designed to occur between the student and CT, little (if any) role is ascribed to the teacher.

Our research provides empirical evidence for an innovation in practice; specifically, a conceptualization of how teachers might implement CT and computer-delivered mathematics instruction to optimize students' learning of mathematics. This work stems from a design-based project, in which our research group's specific role within the larger project was to examine and enhance the mathematics teaching and learning components of a robotics-themed cognitive tutor (CT) program. The program aims to introduce robotics and proportional reasoning to students in 4^{th}-8^{th} grade, as programming the robots involves proportional relationships (e.g., linear distance and turn angle are linear functions of wheel size and motor rotations). Proportional reasoning is a key mathematical idea in middle school (National Council of Teachers of Mathematics, 2006; Lobato, et.al, 2010); hence this program aimed to enhance students' learning of important mathematics through an engaging engineering/robotics context.

As a design study, our work proceeded in three phases. In Phase 1, we reviewed the tutor materials and determined that the vast majority of tasks (97% of all tutor tasks) engaged students in only lower levels of mathematical thinking; specifically, procedures without connections to meanings, concepts, or understanding (Stein, Grover, & Henningsen, 1996). In mathematics education research, procedural knowledge of this type is considered "low cognitive demand" and has been empirically associated with low student achievement in mathematics (e.g., Stein & Lane, 1996; Hiebert & Stigler, 2004). Conversely, declarative knowledge is consistent with high cognitive demand, and research suggests that cognitively challenging tasks, with high-level demands maintained during implementation, are associated with positive student learning (Boaler & Staples, 2008; Stein & Lane, 1996; Tarr et al., 2008).

The CT tasks initially observed by our research team in Phase 1 required students to perform procedures (e.g., multiply or divide to complete a data table) without invoking a conceptual understanding of proportional relationships. In fact, only 2 of 62 original CT tasks (3%) provided students opportunities for higher-level thinking and reasoning. Furthermore, at early implementation sites (prior to our involvement), no learning gains appeared on a test of proportional reasoning (Weaver & Junker, 2004). Driven by our hypothesis that higher-cognitive-demand tasks would increase students' learning, the remainder of Phase 1 consisted of the development and integration of a set of cognitively demanding tasks into the CT system, tasks that engaged students in thinking about the role of unit rates and scale factors in proportional relationships. CT tasks were revised to have high-level demands, with new materials containing 16 high-demand tasks (16/48; 33%) that could engage students in developing a conceptual understanding of proportional relationships and strategies (e.g., unit rates and scale factors). We analyzed CT mathematics instructional materials using existing frameworks developed to examine the cognitive demand of mathematical tasks (i.e., the Task Analysis Guide (Stein, Smith, Henningsen, & Silver, 2009) and shifts in their implementation through lesson phases (i.e., the

Mathematics Task Framework [Stein, Grover, & Henningsen, 1996). We also drew from research delineating students' development of proportional reasoning (Lamon, 2007).

Phase 2 primarily consisted of observations of the implementation of the new, higher-cognitive demand materials using an observation instrument (the Interaction Tracker) that was based on a conceptualization of teaching and learning known as the "instructional triangle" (Cohen, Raudenbush, & Ball, 2003; Stein & Kim, 2012). At one implementation site, researchers noted that instructors engaged students in discussions *away from* the CT screen to help students understand the underlying mathematical ideas (e.g., unit rate and scale factor). These interactions between teachers and students around the mathematics seemed particularly fruitful for impacting students' learning, and distinctly different from interactions noted in other settings. Seeing these types of interactions occurring in only one setting caused the team to consider the possible role of the instructors in the CT program. We hypothesized that different teacher-student-computer interaction styles would generate differences in students' learning, and that different interaction styles may be associated with teachers' pedagogical content knowledge (PCK) of proportional reasoning.

In Phase 3, based on this second hypothesis, we developed materials that introduced teacher-mediation into the system. Specifically, we inserted materials that were designed to guide teacher-student interactions at points where students had just finished learning or dealing with difficult concepts. Specifically, facilitation materials were created that encouraged teachers to draw students' attention back to the declarative knowledge pieces of the program. These materials were meant to foster interactions between students and teacher away from the CT that were still grounded in the unique robot context and that provided opportunities to talk more deeply around the mathematics. In this paper, we present research testing our hypotheses at phases 2 and 3:

1. Did implementation sites using the high-cognitive-demand CT tasks exhibit increases in students' learning?
2. Are different types of teacher-student-computer interactions associated with teachers' level of PCK?
3. Did implementation sites using the high cognitive demand CT tasks and embedded opportunities for interaction (about the mathematics) exhibit increases in students' learning?

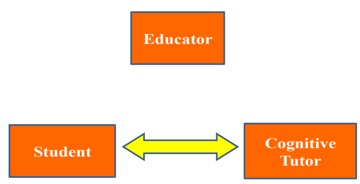
Method

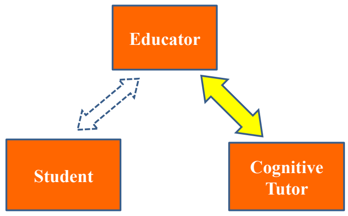
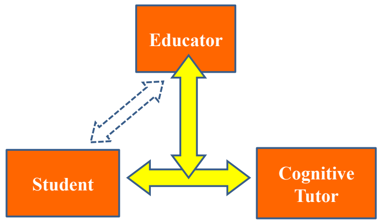
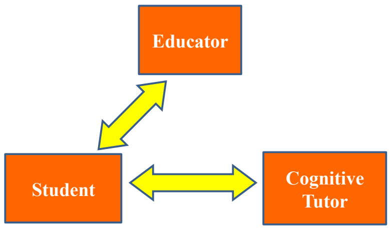
In Phase 2, the project worked with 3 implementation sites representing 111 students, observing the impact of the revised CT materials from phase 1 on learning outcomes and students' interactions with the system. During these implementations, the research team made regular observations and assessed student knowledge by administering a pre-post proportional reasoning written assessment using an equivalent forms design (e.g., Weaver & Junker, 2004). These student pre- and post-test scores were compared using paired-values t-tests.

Teachers in the three Phase 2 implementation sites were observed as they implemented the CT program, and an "Interaction Tracker" (informed by Stein and Kim, 2012) that was developed to represent the observed interactions. The Interaction Tracker was then tested in three additional settings. We compared interaction patterns of teachers with different levels of PCK in proportional reasoning, based on a project-developed assessment of teachers' use of proportional reasoning strategies to solve challenging problems and ways in which they indicated they would support students' use of proportional reasoning strategies. We designed, piloted, and checked the reliability of this assessment. Specifically, we double-coded 7 teacher-PCK tests (3 pilot teachers and 4 project teachers) with 89% exact-point reliability. Teacher-PCK data exists for 8 of 10 facilitators, representing 5 of 6 implementation sites (one facilitator was an expert from the project team). We also examined whether different interaction patterns supported students' engagement in high-cognitive-demand tasks.

During these Phase 2 observations we identified four distinct types of interactions between the teacher, students, and CT (see Table 1). Educators (n = 10) at each of the six implementation sites, through phase 2 and phase 3, were observed by at least one member of the team, during at least two sessions.

<u>Table 1. Interaction patterns</u>

Interaction Pattern	Description	Instructional Triangle Diagram
Cognitive Tutor (CT) Environment as Designed	Students interact with the CT with minimal or no interaction between the teacher and student or teacher and CT. The CT provides all learning opportunities; all math activity occurs between the CT and the student (indicated by the double-headed yellow arrow)	

Interaction Pattern	Description	Instructional Triangle Diagram
Educator Taking Over the CT Environment	The educator (instead of the student) interacts directly with the CT, often physically taking over the computer (e.g., reads CT screen to the student, rephrases questions on the CT, enters responses into the computer). Most or all activity with the CT is filtered through the teacher. Teacher-student interactions are teacher-directed, reducing students' engagement with the mathematics to brief responses.	
Educator Facilitating the CT Environment	The educator addresses procedural or technical aspects of the students' interaction with the CT around mathematics (e.g., calling attention to the need to round to 2 decimal places, suggesting use of the hint button). The mathematical activity remains between the student and the CT, with the educator facilitating this activity. The educator does not address aspects of the student's specific ways of thinking or components of the underlying mathematics not present on the CT screen.	
Educator Facilitating the Mathematics	The educator interacts with the student about the underlying mathematics or about the students' specific mathematical thinking. The interaction is no longer directly about what is happening on the screen. Meaningful mathematical activity occurs between the teacher and student, and then the student uses the mathematics to engage with the CT.	

To examine the impact of an increased role for teachers in the CT environment, we re-designed the materials to include embedded opportunities for teacher-student interactions around the mathematics in Phase 3 of the program. In the original materials, students progressed through a series of computer-delivered, cognitive tutor modules at their own pace. The new structure contained three whole-group discussion points (D1, D2, and D3 in Figure 1) and facilitation materials designed to increase students' engagement with the robot engineering context (D1), the mathematical ideas (D2) (e.g., proportional reasoning, scale factor, and unit rate), and to use the mathematics to accomplish the goals of the robot-engineering context (D3).

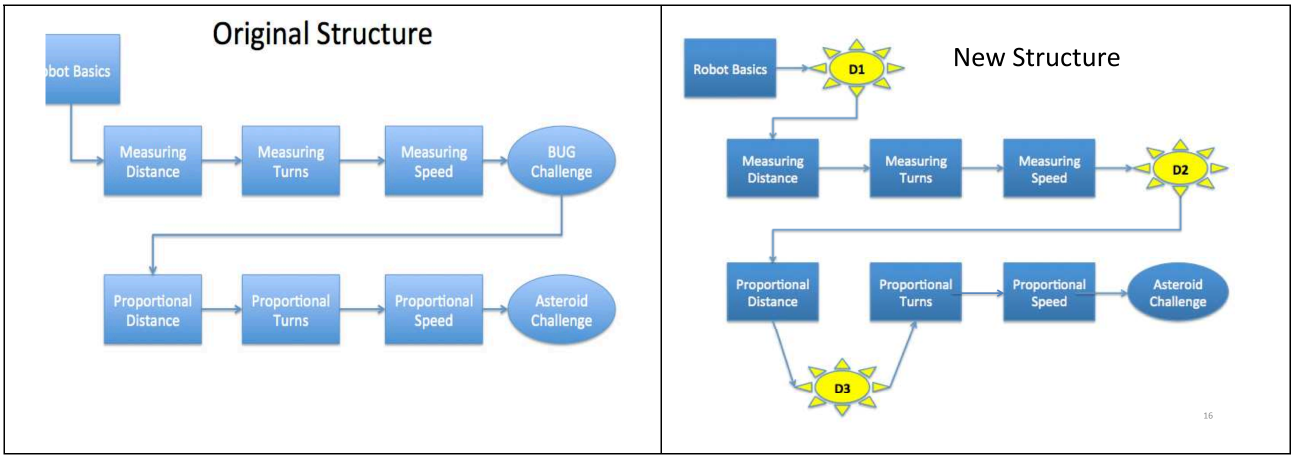


Figure 1. Original and revised structure

In phase 3, a member of the design team piloted the new teacher-mediated materials in an afterschool program (n_4 = 12 students) in grades 5-7. Following this pilot, two teachers from different districts also implemented the new materials (n_5 = 12 students; n_6 = 16 students). Students' work on the project lasted approximately 3 weeks at each site and included students in grades 7-8. Along with the pre/post assessments of students' knowledge, observations were carried out at both sites using the Interaction Tracker.

Findings

Research Question 1. In examining the three implementation sites in Phase 2 that used the high-cognitive-demand CT materials (n = 111 students), students showed no learning gains on the proportional reasoning written assessment (p = .48). Hence, simply incorporating the high-cognitive-demand tasks did not generate the anticipated increases in students' learning.

Research Question 2. Teachers' interaction patterns were examined, and for each teacher, researchers identified a clear main interaction pattern and secondary interaction pattern(s). The 10 teachers were then grouped by their scores on the PCK tests, and a relationship between PCK and interaction pattern appeared to exist (see Table 2).

Research Question 3. In piloting the Teacher-Mediated materials (Phase 3), the instructor in one implementation site was a member of the research team (Site 4; n_4 = 12). In the two school-based implementation sites (n_5 = 12, n_6 = 16), students' pre/post assessments increased (Site 5, 56% to 57%; Site 6, 59% to 64%). When comparing the pre/post scores across all three sites that used the new teacher-mediated materials, including the pilot, we see a significant increase from M=.596 to M = .633, (n=41, p =.04).

Looking across Research Questions 2 and 3 to further explicate the connection between the observed interaction patterns and students' learning, the research team is more deeply examining Group 1 and Group 2 teachers and implementation sites (see Table 2). Preliminary results support the connection between the "facilitating the mathematics" pattern and increased student-learning.

Table 2. Teachers' interaction patterns and pedagogical content knowledge scores

Teacher	Certification	PCK Score	Interaction Patterns
Group 1: *Facilitating the Mathematics* as the Primary Instruction Style			
Site 4	Expert	High PCK	*Facilitating the Mathematics* Facilitating CT Environment Designed CT environment
Site 2 –Teacher	Math	83%	*Facilitating the Mathematics* Designed CT environment Facilitating CT Environment
Site 2 – Student Teacher	Math Pre-Service Teacher	76%	*Facilitating the Mathematics*
Group 2: *Facilitating the Mathematics* as a Secondary Instruction Style			
Site 3 – T2	Math	58%	Facilitating CT Environment *Facilitating the Mathematics* Designed CT environment
Site 3 – T1	Science	56%	Facilitating CT Environment *Facilitating the Mathematics*
Site 6	Technology/Industrial Arts	56%	Facilitating CT Environment *Facilitating the Mathematics*
Group 3: *Facilitating the Mathematics* Not Present			
Site 1 – T2	Elementary	53%	Facilitating CT Environment Taking over the Environment
Site 1 – T1	Elementary	50%	Facilitating CT Environment
Site 5	Technology/Industrial Arts	22%	Designed CT environment
Site 2 - LST	Learning Support	--	Taking over the Environment

Implications

Our work echoes a consistent finding in mathematics education research: cognitively challenging tasks are a necessary but not sufficient condition for promoting students' learning of mathematics, and implementation appears to be key. In our work, revising the CT tasks did not enhance students' learning, but coupling such tasks with implementation that maintains high cognitive demands (e.g., as enacted in the "Facilitating the Mathematics" interaction pattern and as designed into the teacher-mediated materials) was essential for increasing students' proportional reasoning strategies and understanding of proportional relationships. This represents a shift in how the practice of using CT's in the classroom has been looked at in the past.

The role of teachers' pedagogical content knowledge suggests the need for professional development around the teaching of important mathematical ideas. Crafting the types of interactions that facilitate the mathematics in CT and computer-delivered learning environments requires a deep understanding of the underlying mathematical ideas that is often not included as part of current CT resources. Building this capacity in teachers who will be implementing this CT program shows promise in laying a foundation for quality mathematics-based interactions with students.

Finally, across sites and contextual factors, the addition of teacher mediation to the system had a positive impact on students' ability to learn proportional reasoning. This finding has general implications for reconsidering the "designed" role of the teacher in CT or computer-delivered instructional settings. Teachers acting to "facilitate the mathematics" may promote greater students' learning than if the CT or computer is assumed to direct the teaching and learning in a "teacher-less" environment.

References

Anderson, J. R., Corbett, A. T., Koedinger, K. R., & Pelletier, R. (1995). Cognitive tutors: Lessons learned. *The journal of the learning sciences*, *4*(2), 167-207.

Boaler, J., & Staples, M. (2008). Creating mathematical futures through an equitable teaching approach: The case of Railside School. The Teachers College Record, 110(3), 608-645.

Brusilovsky, P., & Peylo, C. (2003). Adaptive and intelligent web-based educational systems. International Journal of Artificial Intelligence in Education, 13(2), 159-172.

Cohen, D. K., Raudenbush, S. W., & Ball, D. L. (2003). Resources, instruction, and research. Educational Evaluation and Policy Analysis, 25(2), 119-142.

Hiebert, J., & Stigler, J. W. (2004). Improving Mathematics Teaching. *Educational leadership*, *61*(5), 12.

Henningsen, M. & Stein, M. K. (1997). Mathematical tasks and student cognition: Classroom-based factors that support and inhibit high-level mathematical thinking and reasoning. *Journal for Research in Mathematics Education*, *28*, 524-549.

Koedinger, K. R., & Corbett, A. T. (2006). Cognitive tutors: Technology bringing learning science to the classroom.The Cambridge handbook of the learning sciences, 61-78.

Lamon, S. J. (2007). Rational numbers and proportional reasoning: Toward a theoretical framework for research. Second handbook of research on mathematics teaching and learning, 1, 629-667.

Lobato, J. & Ellis, A. (2010). *Developing Essential Understanding of Ratios, Proportions & Proportional Reasoning: Grades 6-8*. Reston, VA: National Council of Teachers of Mathematics.

National Council of Teachers of Mathematics (NCTM). (2006). Curriculum focal points for prekindergarten through grade 8 mathematics: A quest for coherence. Reston, VA: NCTM.

Stein, M. K., Grover, B. W., & Henningsen, M. (1996). Building student capacity for mathematical thinking and reasoning: An analysis of mathematical tasks used in reform classrooms. American educational research journal, 33(2), 455-488.

Stein, M. K., & Kim, G. (2012). The role of mathematics curriculum materials in large-scale urban reform: An analysis of demands and opportunities for teacher learning. In Remillard, J. T., Herbel-Eisenmann B. T., & Lloyd, G. M. (Eds), *Mathematics teachers at work: Connecting curriculum materials and classroom instruction,* (pp. 37-55). New York, NY: Routledge Taylor &Francis Group.

Stein, M. K., & Lane, S. (1996). Instructional tasks and the development of student capacity to think and reason: An analysis of the relationship between teaching and learning in a reform mathematics project. Educational Research and Evaluation, 2(1), 50-80.

Tarr, J. E., Reys, R. E., Reys, B. J., Chávez, Ó., Shih, J., & Osterlind, S. J. (2008). The impact of middle-grades mathematics curricula and the classroom learning environment on student achievement. Journal for Research in Mathematics Education, 247-280.

Weaver, R., & Junker, B. W. (2004). Model specification for cognitive assessment of proportional reasoning.

