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Implementation Study Results of an Efficacy Trial of the Cognitive Tutor Geometry Curriculum

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Implementation Study Results of an Efficacy Trial of the Cognitive Tutor Geometry Curriculum

Results from the National Assessment of Educational Progress (NAEP) suggest that schools continue to struggle with improving mathematics achievement for high school students. Despite recent small gains for fourth and eighth graders (Lee, Grigg, & Dion, 2007), NAEP math scores for 17 year-olds have remained stagnant from 2004 to 2008 and have shown no significant improvements in racial and ethnic achievement gaps (Rampey, Dion, & Donahue, 2009). Many schools and districts are attempting to improve mathematics achievement by adopting new curricula that embed research-based knowledge about how students learn and how particular types of instruction can support that learning (Remillard, 2005). Curriculum adopters, however, lack sufficient research knowledge about curriculum effectiveness to make informed decisions about which curricula are the most promising for their context (National Research Council, 2004; Schoenfeld, 2006).

The National Council of Teachers of Mathematics (NCTM) Research Committee (2008) and the National Research Council (NRC) report, "On Evaluating Curricular Effectiveness: Judging the Quality of K-12 Mathematics Evaluations" (2004) have called for more rigorous evaluations of curricular effectiveness that include detailed implementation studies documenting not only whether particular programs work, but also the character of their implementation and the conditions under which they were implemented. When impact evaluations yield positive results, implementation studies can help program adopters understand and provide the conditions for effectiveness demanded by a particular curriculum (National Research Council, 2004). Similarly, when impact evaluations yield negative results, findings from such studies can help program adopters decide whether to invest more to support implementation of a promising curriculum—with the hopes of improving its effects—or to abandon it for a more effective alternative.

This article responds to these calls for more information about the character of implementation in context by reporting implementation results from a randomized, controlled trial of the Cognitive Tutor Geometry curriculum in Baltimore County Public Schools (BCPS). We decided to conduct a trial of this particular curriculum because it had shown promise in quasi-experimental studies, and a related curriculum, Cognitive Tutor Algebra I, was shown to have significant positive effects in a randomized field trial (Ritter, Kulikowich, Lei, McGuire, & Morgan, 2007). We selected Baltimore County as the site for the study because it was a district needing to make substantial improvements in students' mathematics achievement and was considering adoption of a new curricula as a strategy for meeting that objective.

However, our impact study found that the geometry curriculum had a significant negative effect on student achievement. Specifically, student achievement on the district's final exam was 0.19 standard deviation units lower in the treatment group than in the control group, which had been exposed to the district's standard geometry curriculum (Author et al., 2010). This finding raises several questions. First, to what extent did teachers implement the curriculum as intended? Second, which facets of curriculum implementation were most strongly linked to student achievement? Finally, what contextual factors were associated with the quality of implementation? This article addresses these questions and ends with recommendations for policymakers, curriculum developers, and researchers.

Description of the Curriculum Intervention

The Cognitive Tutor Geometry curriculum, published by Carnegie Learning, Inc., is a complete course designed to promote understanding of geometric concepts and principles and to enhance abstract and spatial reasoning skills. The curriculum includes two components: teacher- guided classroom instruction (60% of instructional time), and individualized, computer-guided instruction using Carnegie Learning's tutorial software (the remaining 40% of instructional time). The classroom instruction and lab portions of the course are typically carried out in large blocks of time, such as whole class periods.

The Cognitive Tutor software was designed by researchers at Carnegie Mellon University based on John Anderson's ACT-R computational theory of thought (Anderson, 1983), and draws on research from several disciplines, including artificial intelligence, cognitive psychology, and human-computer interaction. The software contains a model of the processes students follow when solving problems, including multiple paths toward correct solutions and common misconceptions that lead to incorrect solutions. By tracing student progress in this model, the software intervenes with well-targeted feedback when the student makes errors, and continuously updates its assessment of skill mastery by considering the student's correct actions, errors, and hint requests. The software's adaptive nature is designed to provide individualized instruction to address students' specific needs. Students are presented with challenging, multi-step problems that reflect real-world situations and provide opportunities for students to build on prior knowledge and progress from concrete to abstract thinking.

In addition to the software, the curriculum provides student and teacher textbooks and workbooks, and detailed guidelines for instructors on structuring classroom time through learner-centered activities such as independent problem solving, cooperative-learning group work, and student presentations. Typically, teachers receive three days of formal training by Carnegie Learning staff prior to curriculum implementation and an additional follow-up day after implementation begins. Teachers have access to an online professional learning community where they can access resources, share ideas, and seek feedback. Carnegie Learning also provides regionally based staff who visit schools to provide coaching assistance to teachers in their classrooms. All of these forms of assistance provide support for both software and classroom-based activities.

Research Questions and Analytical Framework

The research questions we address in this article are as follows: 1) What was the nature of implementation in treatment and control classrooms? 2) How is implementation related to student achievement? 3) What factors might explain the quality of implementation?

Our analytical approach to answering these questions responds to recent calls for curriculum-specific measures of textbook integrity (Brown, Pitvorec, Ditto, & Kelso, 2009; Chval, Chávez, Reys, & Tarr, 2008; Huntley, 2009) that recognize that high-quality implementation involves mutual adaptation in which teachers might appropriately alter the specifics of the written lesson to address specifics of their context while still honoring the underlying principles of the curriculum design (Ball & Cohen, 1996; McLaughlin & Mitra, 2001). At the same time, teachers may adopt curriculum materials without teaching in ways that align with the curriculum developers' pedagogical orientation (Chávez, 2003; Chval, et al., 2008; Tarr, et al., 2008). Chval et al. (2008) outline "three essential components of textbook integrity: (a) regular use of the textbook by the teacher and students over the instructional period, (b) use of a significant portion of the textbook to determine content emphasis and instructional design over the school year, and (c) utilization of instructional strategies consistent with the pedagogical orientation of the textbook" (p. 72).

Because the Cognitive Tutor curriculum includes more than just textbooks, but also tutorial software and student workbooks, the concept of textbook integrity that we employ in this analysis includes measures of fidelity in use of all of the curriculum materials. We created an implementation rubric that would allow us to quantify fidelity of implementation along 18 different dimensions related to: scope and sequence, time in the computer lab, use of curriculum workbooks, use of curriculum homework materials, regular assessment, collaborative learning activities, making connections with prior knowledge and experiences, assignment of formal presentations, individualized learning, student explanations, student collaboration, student delivery of presentations, student engagement in classroom, student engagement in computer lab, teacher assistance, closing an activity, grading, and use of Cognitive Tutor software reports.

Our rubrics are similar to analytical tools that were developed to measure implementation of mathematics curricula, such as Math Trailblazers (Brown et al., 2009), Connected Mathematics and MathThematics (Hord, Stiegelbauer, Hall, & George, 2006). On these analytical tools, "various dimensions of instruction are classified along a continuum from being very close to what the developer had in mind to a distant zone for which what is being done would be far from the developer's intent. In this way, [the tools] yield continuous measures along several dimensions of instruction, rather than a dichotomous judgment of whether instruction has been faithful to the authors' intents" (Huntley, 2009, p. 358). For example, according to the rubric, there was little to no evidence of implementation of the dimension of making connections with prior knowledge and experiences when "the teacher does not encourage students to make connections (e.g., teacher makes connections once or less during a class period)", some evidence when "the teacher implies that there could be connections to students prior knowledge and experiences but does not give examples or help students with making these connections (or only makes connections a couple of times)", and strong evidence when "throughout the class, the teacher helps students to make connections (e.g., from the context of the problem to the mathematical representation, between different mathematical representations, to previous learning, to software problems, or to future work)".

The process we used to develop the implementation rubric began with two researchers attending the three-day Cognitive Tutor Geometry training for teachers and recording trainers' descriptions of what constituted appropriate implementation, including messages about when and how teachers were expected to use their judgment to deviate from the planned curriculum. We drew on these notes and a thorough review of the curriculum materials to create a first draft of the implementation rubric, which we then provided to the developers for feedback. We revised the rubric accordingly and then jointly observed three separate lessons with a Carnegie Learning representative. We discussed the observed lessons in relation to the rubric and added further clarification to the rubric in some places to improve reliability of the ratings. Research team members also attended the training provided to teachers participating in the study and confirmed that Carnegie Learning was giving teachers in our study the same messages about expectations for implementation.

Research Methods

Setting and Study Design

The study was carried out in eight high schools in BCPS, which is located in the urban fringe of Baltimore and serves students from a wide range of racial/ethnic and socioeconomic backgrounds. At the time of the study, the district had 25 high schools, with a total enrollment of about 32,000 students. In the eight participating high schools, the average minority enrollment rate was 46%, and 26% of students qualified for free or reduced-price meals (FARMS).

Data collection was conducted during the 2005-06, 2006-07, and 2007-08 academic years. The eight study schools arranged their schedules such that two participating teachers were scheduled to teach geometry concurrently during two class periods. During the first period, we randomly assigned one teacher to teach the Cognitive Tutor Geometry treatment-group curriculum while the other taught the BCPS control-group curriculum. In the later period, the teachers switched curricula. As such, the study involved two teachers and four classes from each participating school each year. Students whose schedules called for them to take geometry during one of the two class periods under study were randomly assigned to either a treatment- or control-group classroom, regardless of their grade level or other characteristics. The study included a total of 19 teachers, 11 of whom participated for only one year, five of whom participated for two years, and three of whom participated for all three years. The student sample used for the analyses in this article consists of 699 students, 350 of whom received the treatment curriculum, and 349 of whom received the control curriculum (see Author et al., 2010, for additional details).

Data Collection and Measures

Classroom instruction measures. To monitor implementation of the treatment curriculum and measure instructional practices in both treatment and control classrooms, researchers visited each teacher in the study three times per year by appointment. During each visit, researchers conducted structured teacher interviews and observed each teacher's treatment and control classrooms for an entire class period. At least one of the three treatment classroom observations was conducted during a class period during which students were engaging with the Cognitive Tutor software. The researchers recorded a running narrative of teaching and learning. Subsequent to the observation, researchers rated each class according to the implementation rubric and recorded justifications for each rating, which permitted subsequent data cleaning to ensure consistency across raters and years. Scores of one or two indicated that there was little to no evidence that practices related to that dimension were being implemented, while scores of three or four indicated some evidence, and scores of five or six indicated strong evidence.

To ensure consistency in classroom observations, all researchers participating in classroom observations attended Carnegie Learning's three-day training sessions for teachers, followed by three days of observation and interview training. During this training, the team jointly observed five different classrooms and compared individual ratings of these classrooms. For the last classroom observed, we calculated Cohen's kappa, which ranged from 0.8 to 0.85 each year, suggesting strong agreement among raters.

To summarize these ratings, we averaged each teacher's scores on each dimension for each academic year[1]. We then combined 16 of the 18 teaching practice dimensions into four unweighted composite implementation measures: 1) learner-centered practices, 2) student participation, 3) materials fidelity, and 4) computer lab use. In addition to constructing the unweighted composites, we used principal components analysis with varimax rotation to construct an alternative set of weighted composites, but the weighted principal components did not lend themselves to intuitive interpretations, so we used the unweighted composites in the analyses. Like the underlying dimensions, the values of each composite ranged from 1, signifying weak compliance with curriculum specifications, to 6, signifying strong compliance.

Student achievement measures. Student achievement in geometry was measured using the district's required geometry final examination, administered at the end of the course. The examination included 30 multiple-choice items and 11 extended-response items. Extended-response items were scored by experienced geometry teachers hired by the authors. To increase the precision of our estimates, our analysis also controlled for students' prior achievement in mathematics using a 25-item, multiple choice, end-of-course algebra examination published by Educational Testing Service (2004). This pretest was selected because algebra precedes geometry in the district's curriculum. Pretest scores in the sample were low on average. Out of 25 possible points, the mean raw score was 8.3, with a range from 0 to 19. Both tests were standardized to a mean of 0 and a standard deviation of 1.

Findings on the Nature of Implementation in Treatment and Control Classrooms

As mentioned above, treatment group students scored significantly lower on the posttest than control group students. The negative effect raises the question of whether the curriculum was implemented as intended by the curriculum developers. Our analysis of implementation ratings found that:

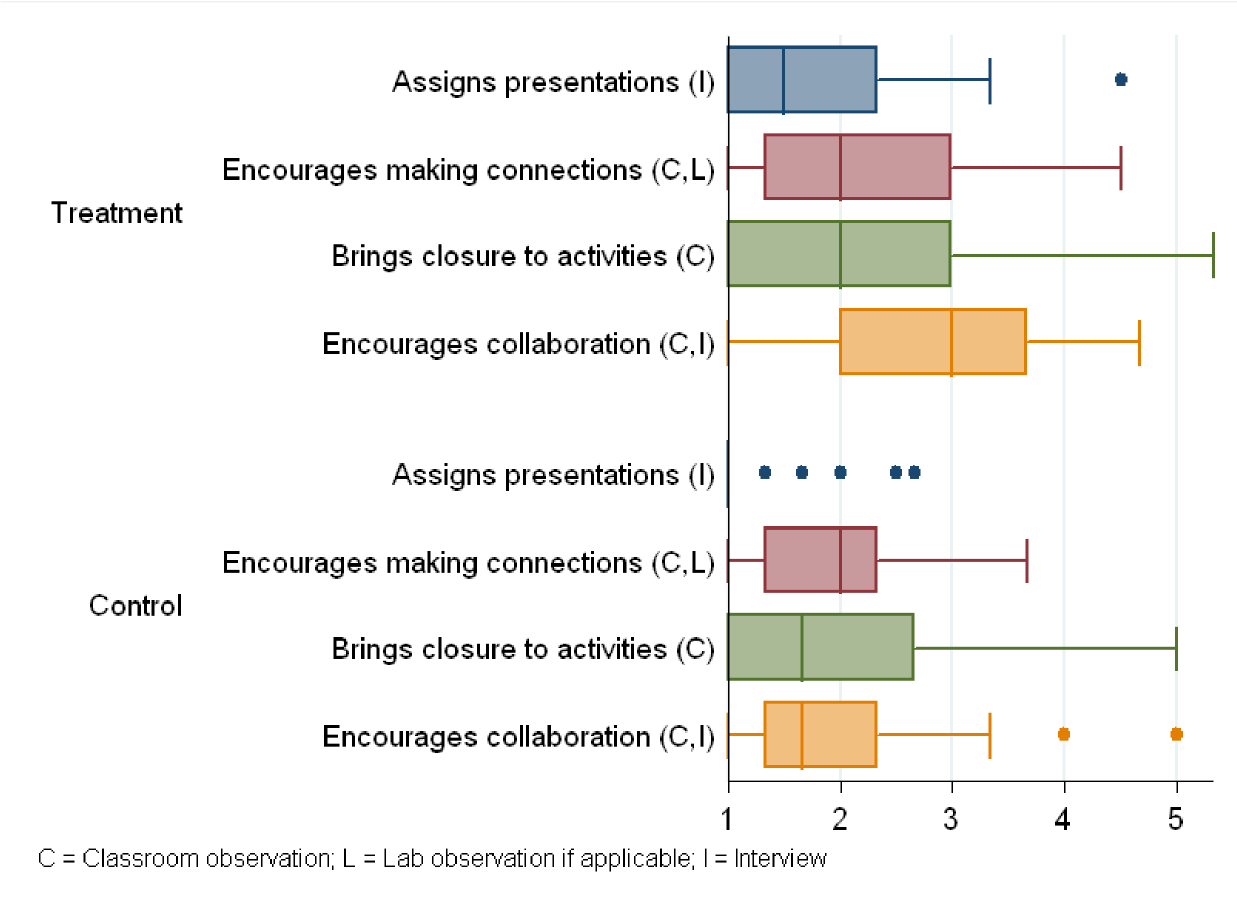
- Implementation of learner-centered practices was slightly higher in treatment classrooms, but relatively low overall.
- Student participation levels were similar—and modest—in both treatment and control classrooms.
- Fidelity to Cognitive Tutor materials was reasonably high, ranging from medium to high.
- Computer lab use was relatively consistent with curriculum guidelines.

The sections below elaborate on these findings.

Implementation of Learner-Centered Practices

Our first composite variable, learner-centered practices, captured the extent to which a teacher, during a given class period and school year: assigned presentations, encouraged students to make connections among concepts, brought closure to activities, and encouraged students to collaborate with one another. All are teaching strategies explicitly prescribed by the Cognitive Tutor curriculum, though they can also be measured in non-treatment classrooms. Developers expected teachers to use all of these. Figure 1 presents box plots showing the distribution of each component dimension in both treatment (top) and control (bottom) classrooms, on a 1 to 6 scale, with 1 indicating very low use of this strategy and 6 indicating very high use. The median level of three of the dimensions was higher in treatment classes, as one might expect, though the extent to which teachers encouraged students to make connections among ideas or concepts was virtually identical in treatment and control classrooms.

Figure 1: Learner-Centered Practice indicators (n=30 treatment & 30 control classes)



Carnegie Learning suggests that teachers assign presentations—in which students are expected to share ideas, strategies, and knowledge—in at least four out of every ten class periods. An example of an intended presentation is included later in this paper, in Figure 7. However, we found low implementation of this practice across our treatment classrooms, with the majority of teachers assigning presentations two times or fewer per quarter. Nevertheless, this degree of implementation was still greater than in control classrooms, where most teachers—except for a few outliers—never assigned presentations.

The Cognitive Tutor curriculum materials also emphasize "making connections with prior knowledge and experiences." We found that the median implementation of this strategy was low, at 2 on a 6 point scale, in both treatment and control classrooms. A rating of 2 suggests that the teacher encouraged students to make connections one time or fewer each class period. The distribution of the practice had a wider upper range in treatment classrooms, suggesting that at least some teachers encouraged connections more often with the Cognitive Tutor curriculum than with the control curriculum.

Bringing closure to activities—by asking summary wrap-up questions or reviewing student work in ways that ensured students understood the mathematics behind their solutions—was slightly more evident in treatment classrooms than in control classrooms, with a median of 2 in the former and approximately 1.6 in the latter. However, these medians still fell on the low end of the scale, meaning that teachers typically did not attempt to bring closure to activities or did not do so in ways that checked for students' understanding. Students were often allowed to work until the bell rang, a point we return to in the discussion of Figures 8 and 9 below.

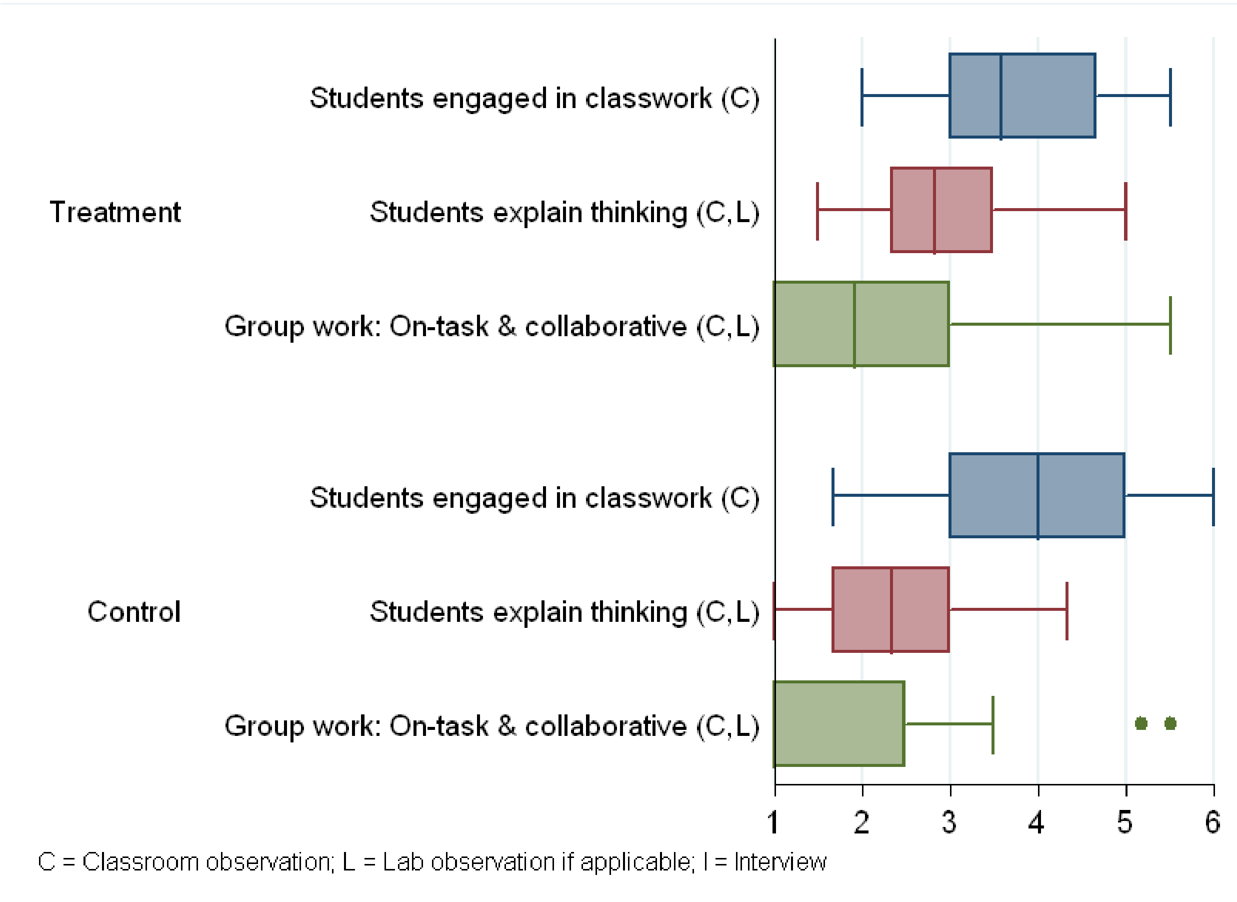
The largest difference we found in learner-centered practices between treatment and control classrooms was in the extent to which teachers encouraged student collaboration. The median rating for Cognitive Tutor classrooms was a 3, suggesting that the median teacher was assigning, monitoring, and supporting collaborative learning activities in approximately 30 to 80% of classroom lessons. This level of implementation did not meet Carnegie Learning's expectation that collaborative learning would be used during 80% of classroom lessons, but it was substantially higher than in the median control classroom, where collaborative learning was reportedly assigned during fewer than 30% of classroom lessons and was thus infrequently witnessed by our observers.

Student Participation

The next composite, student participation, was an unweighted average of three components that reflect students' actions in the classroom, with a focus on behaviors that are encouraged by the Cognitive Tutor curriculum in both the computer lab setting and the regular classroom setting. The box plots in Figure 2 illustrate the distributions of these components in treatment and control classrooms. They suggest, notably, that median student engagement was higher in the control classrooms than in the treatment classrooms, but that engagement generally fell in the medium range, with interquartile ranges between about 3 and 5 in both treatment and control classes. This suggests that the majority of students were engaged the majority of the time in both types of classrooms. A medium rating also suggests that a handful of students were off-task for a majority of the time. We also found the median observed frequency of students explaining their thinking was almost as high in control classes as in treatment classes, but it was still borderline low/medium in both cases, suggesting that, at best, there tended to be only some examples of students explaining their thinking and that these instances tended to be teacher-prompted. We did not observe as many examples of students routinely explaining their thinking (by describing the process they used, solution strategies tried and discarded, or alternative solutions) to group members or the whole class as we did in the high-fidelity implementation example described above.

When students were assigned to work in groups, we found that they tended to be distracted and did not show real signs of collaboration in either the treatment or control classrooms, although they were slightly more collaborative in treatment classrooms.

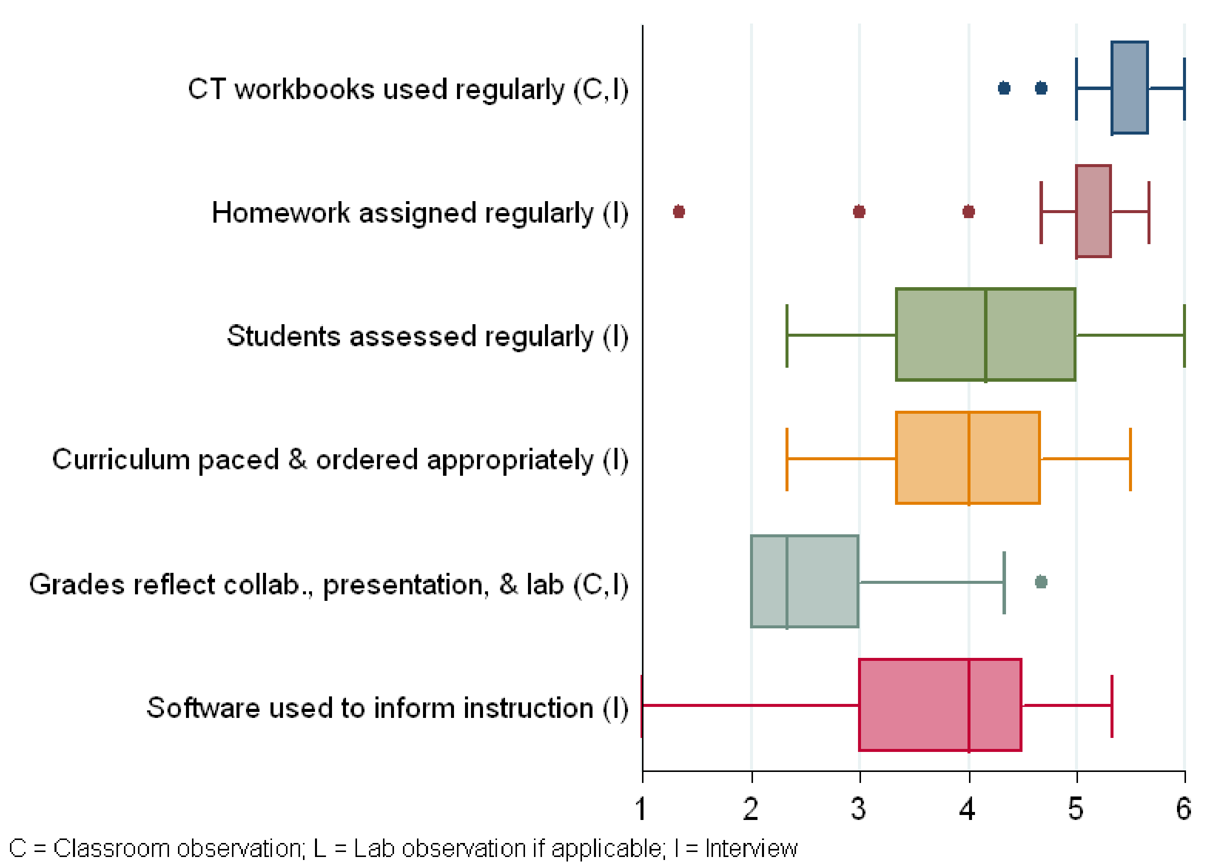
Figure 2. Student Participation indicators (n=30 treatment & 30 control classes)



Fidelity in Implementation of Cognitive Tutor Materials

The next composite, materials fidelity, was based on six dimensions that were only observed in treatment classrooms because they were not applicable to control classrooms. The box plots in Figure 3 suggest that curriculum compliance was high—with medians between 5 and 6—regarding regular use of the Cognitive Tutor workbooks and regular assignment of homework. Implementation on three of the dimensions tended to be at medium levels: teachers were assessing students, but not as regularly as Carnegie Learning suggests; they were attempting to follow the prescribed pacing and ordering, but often fell behind on pacing; and they were using the software to inform instruction, but not in the more sophisticated ways that Carnegie Learning had demonstrated during training. Carnegie Learning suggests that teachers regularly access the Cognitive Tutor software reports and adjust or individualize their teaching accordingly, but teachers tended only to access the reports at the end of marking periods for the purposes of generating grades. The lowest area of compliance in Figure 3 was the extent to which teachers assigned grades that explicitly reflected student collaboration, computer lab use, and presentations. Carnegie Learning recommends that grades reflect these elements and that students be made aware of this grading practice. However, grading standards often did not place emphasis on student collaboration or presentations. In many cases this may be because the teachers were not implementing these practices as intended by Carnegie Learning. Even when the grades did reflect these elements, students were not necessarily made aware of this practice.

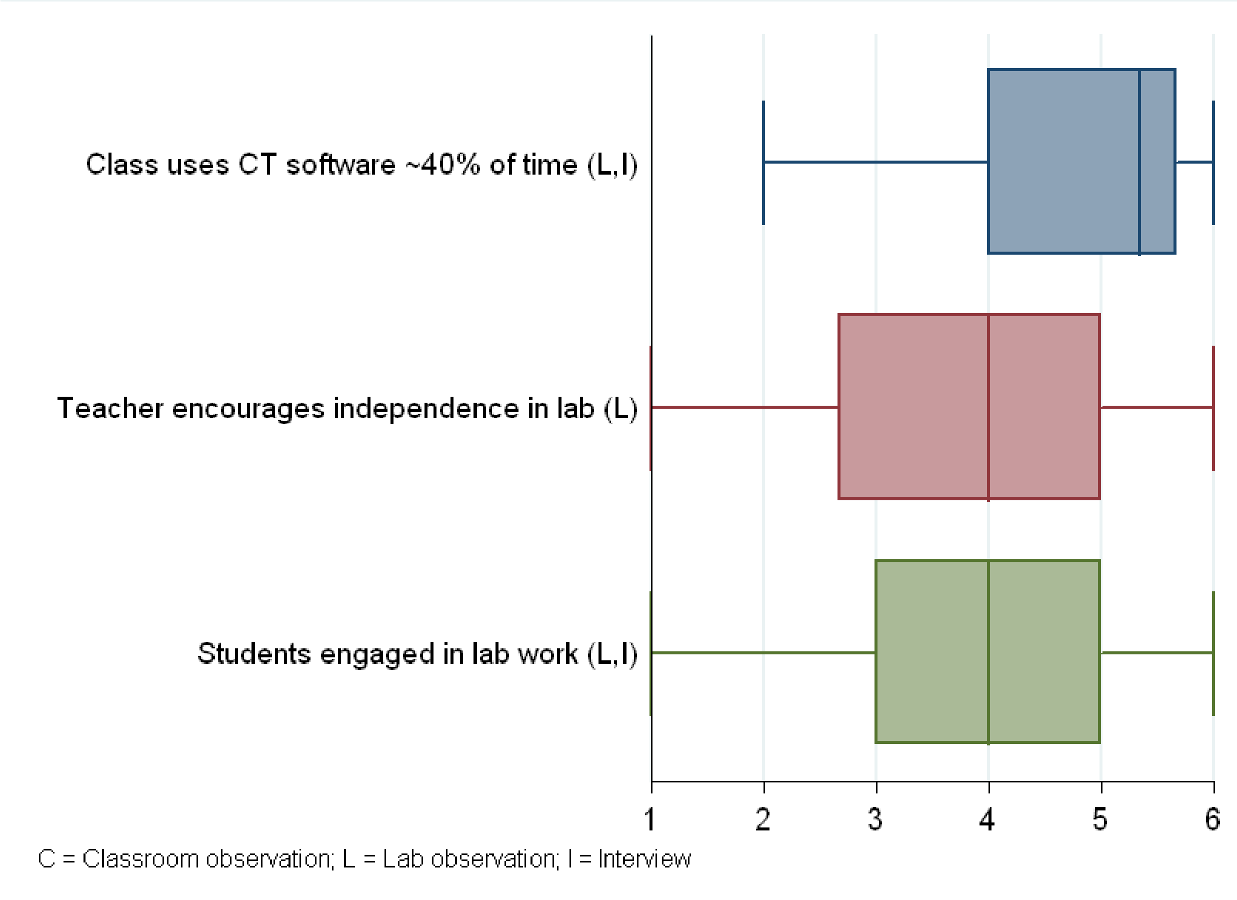
Figure 3. Materials Fidelity indicators (n=30 treatment classes)



Computer Lab Use

The computer lab use composite was also based on dimensions only observed in treatment classrooms. The components of computer lab use are shown in Figure 4, where we observed that most teachers complied with the guideline that 40% of class time be devoted to students' self-paced use of the Cognitive Tutor software. Median implementation of this practice was approximately 5.4. Student engagement and teacher encouragement of computer lab work were also observed with moderately high frequency, with median implementation levels of 4 for each component.

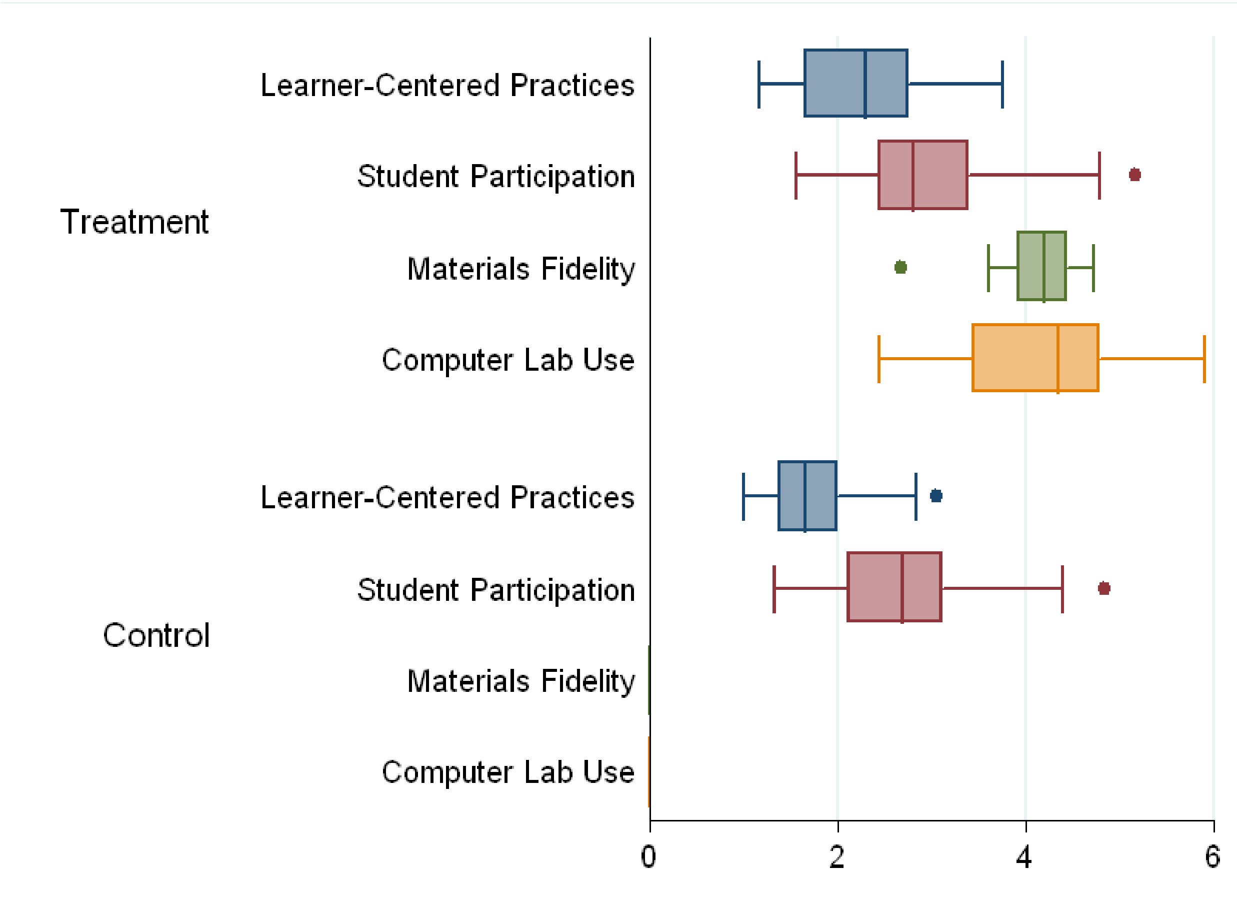
Figure 4. Computer Lab Use indicators (n=30 treatment classes)



Classroom Instruction Composites

Figure 5 summarizes the distribution of the four instructional composites detailed above. These composites were used in the achievement analysis discussed in the following section. Having averaged the components of each composite, we found that fidelity of implementation of the curriculum materials and computer lab was moderately high. Implementation of learner-centered practices was fairly low in treatment classrooms, but slightly higher than implementation of the same practices in control classrooms. Student participation was moderately low in both the control and treatment classrooms.

Figure 5. Distributions of the four instructional composite variables (n=30 treatment & 30 control classes)



Relationship between Implementation and Student Achievement

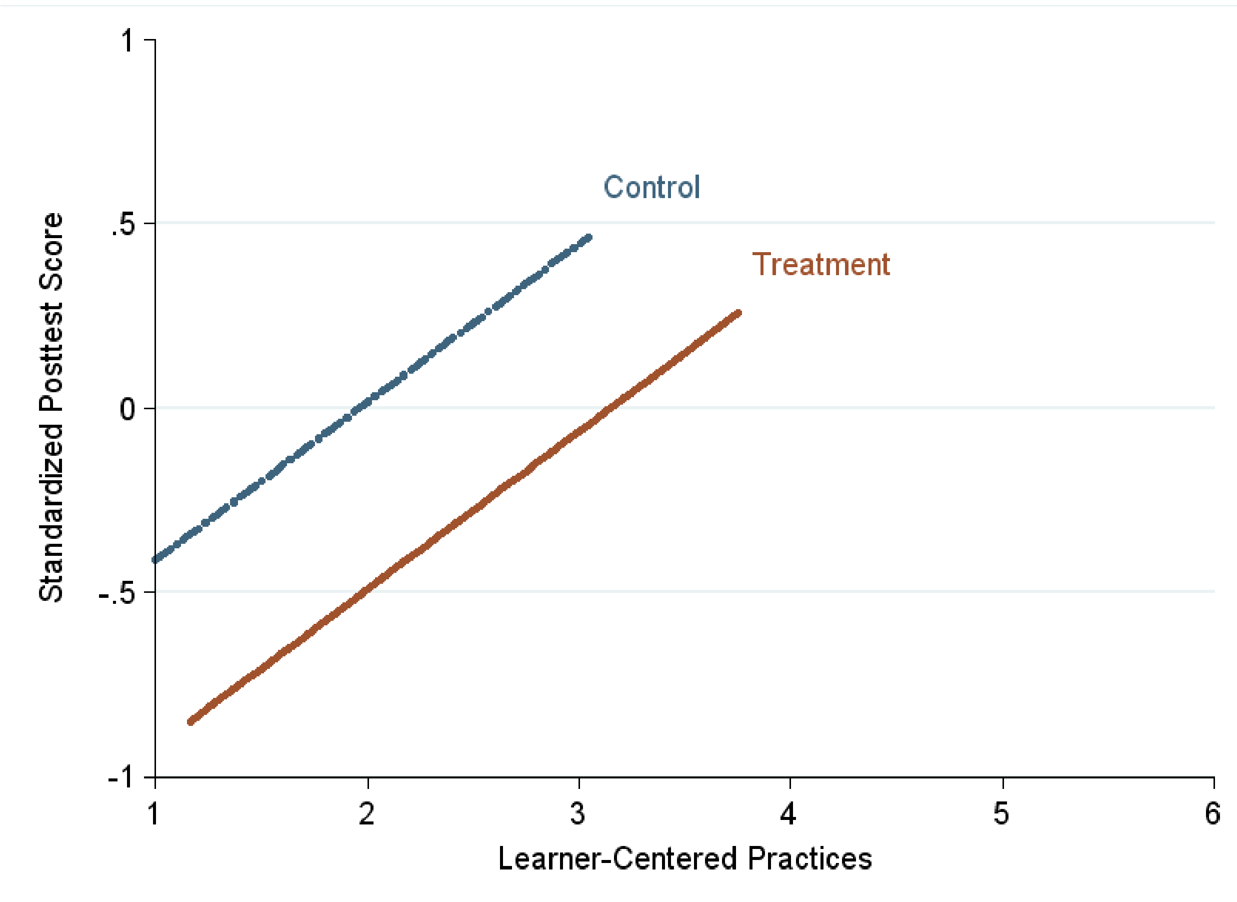
To address our second research question regarding how teachers' implementation of the Cognitive Tutor curriculum is related to students' achievement, we conducted two types of analyses: first, correlational analyses between curriculum implementation and students' geometry achievement, and second, grounded theory analyses of classroom observation records.

Correlational Analyses

Here, we summarize and reflect on results presented in detail in Author et al. (2010). The results are correlational and therefore cannot be interpreted as causal. Moreover, because the composites were measured at the classroom level, with only 30 treatment and 30 control classes in the analysis, we had very limited statistical power to detect even correlational relationships between classroom practices and student achievement—particularly for the implementation composites measured only in the 30 treatment classes.

Bearing in mind these limitations, we found that two of the four instructional composites showed substantial positive relationships to students' geometry achievement, holding constant individual and classroom-average pretest scores and classroom average FARMS eligibility.[1] Specifically, an additional unit of learner-centered practices on the six-point scale was associated with an additional 0.43 standard deviation units of student achievement in geometry at the marginal ten-percent level of significance (p=0.06). Importantly, this relationship did not differ significantly between treatment and control classes, meaning that the positive relationship between learner-centered practices appeared to be independent of the curriculum used. This relationship is illustrated in Figure 6, in which the estimated slope of the relationship between learner-centered practices and student achievement is the same regardless of whether these practices were implemented in treatment or control classrooms.

Figure 6. Fitted effect of Learner-Centered Practices on student achievement in treatment and control classes (n=699 students; 60 classrooms)



Among treatment classrooms, we also estimated that an additional unit of Materials Fidelity on the six-point scale predicted an additional 0.45 standard deviation of student achievement. However, this analysis had very limited statistical power because Materials Fidelity was observed only in the Cognitive Tutor classrooms (n=30 in the analytic sample), and the relationship was not statistically significant at conventional levels (p=0.11). Thus it is not depicted graphically here and should be interpreted with caution.

In contrast, we found no evidence of a relationship between student achievement and either the Student Participation or Computer Lab Use composites. The coefficients associated with both composites were similar to and statistically indistinguishable from 0. In addition, there was no evidence that the relationship between Student Participation and student achievement differed in treatment and control classrooms.

Grounded Theory Analysis

To further explore whether and how implementation influenced student achievement, we conducted a grounded theory analysis (Creswell, 1998) of narrative observation notes. Over the course of the study, observers wrote reflective memos and engaged in debriefing conversations to generate hypotheses about how implementation might be influencing student engagement and achievement. After preliminary student achievement analyses became available, we also generated hypotheses specifically with regards to how the curriculum might be generating a negative effect on student achievement. We then revisited the narrative accounts of our observations to search for confirming and disconfirming evidence for our hypotheses.

We found that the cognitive demands of the curriculum coupled with poor implementation of learning-centered instructional practices seemed to limit students' ability to engage with the mathematical ideas. In Appendices A, B and C, we present three vignettes that illustrate how the curriculum and instructional practices interacted to create different learning experiences for students in three classrooms. According to Miles and Huberman (1994), "a vignette is a focused description of a series of events taken to be representative, typical, or emblematic in the case" (p. 81). Appendix A provides an example from the high-fidelity classroom we visited as part of our implementation rubric development process. This school was in a different district; it had a similar percentage of students qualifying for FARMS (28 percent compared to 26 percent in the study sample) and a greater percentage of minority students (71 percent compared to 46 percent in the study sample). Despite a slightly different student population, this example is valuable because the curriculum developers selected it themselves as emblematic of the intended curriculum and it thus serves as a useful anchor for understanding the other vignettes.

Appendix B provides an example of a typical treatment classroom and Appendix C provides an example of the same teacher in a typical control classroom. Although the observers selected these vignettes, we confirmed that they are typical in that their implementation ratings generally match the median ratings for both types of classrooms. We chose to highlight implementation examples from the regular classroom setting rather than the computer lab setting because the curriculum called for students to spend more time (60 percent) in the classroom setting and because it allows us to illustrate contrasts to the control classroom (which did not use the computer lab). However, we did find similar patterns of low implementation of learner-centered practice in narratives from the computer lab settings.

The example in Appendix A represents high-fidelity in not only material use but also in implementation of learner-centered practices. For example, the teacher effectively assisted students in making connections between their own lives, the sailboat race problem, and the mathematical ideas related to triangles. She also had classroom norms and routines (such as desk configurations, standing group assignments, and expectations for group participation) that facilitated student collaboration. She also assessed student understanding and brought closure to the lesson by having the groups present their work. Throughout the lesson, the teacher facilitated students' ability to engage in the mathematical ideas by scaffolding the prior knowledge and connections they needed to understand the problem and holding students accountable for supporting each others' learning. This illustration of how the developers intended their curriculum to be implemented provides a useful contrast to explain how the example of a typical treatment classroom fell short of these intentions.

The examples from our study classrooms (in Appendices B and C) fit with the overall implementation findings that we described at the beginning of the section. That is, the teacher in the treatment classroom example typified the broader trend of using the Carnegie Learning materials and making more of an effort to support collaborative learning and other learner-centered practices in the treatment classroom than she did in the control classroom. However, she also typified the larger group in that she was unsuccessful in implementing these practices at the high levels intended by the curriculum developers. In both classes, she faced significant problems with student engagement.

Further analyses of our observation narratives suggest that these classroom examples typify the broader sample in other ways as well. We found that when students were faced with the Cognitive Tutor Geometry curriculum, they were more likely to become "stuck" than students facing the control class curriculum. A comparison of the assignments suggest this should not be surprising given that the Cognitive Tutor assignments tend to ask complex real-world mathematics problems while the assignments in control classrooms tend to ask simple straightforward procedure questions. Unlike in the high-fidelity classroom, teachers in the treatment classrooms did not tend to provide introductions to lessons that assisted students in making connections to prior knowledge and life experiences that might have helped them to make sense of the word problems. Also unlike the high-fidelity classroom, students in the treatment classrooms were unlikely to seek much support from other students when they became stuck. This may have occurred because they believed their peers lacked sufficient mathematical knowledge to help them and/or because their teacher did not implement strategies to hold students accountable for collaborating with each other. We explore possible reasons for the overall low implementation of the learner-centered practices in the following section.

Grounded Theory Findings to Explain Quality of Implementation

In this section, we report findings regarding variables that enabled and hindered implementation of the Cognitive Tutor geometry curriculum. In particular, we provide explanations for why implementation of learner-centered practices tended to be low across our study classrooms. Similar to the previous analysis, we used a grounded theory approach (Glaser & Strauss, 1967) to identify themes emerging from our data. This process led us to examine the following factors, many of which have also been identified by prior research: teacher buy-in, administrative support, type and intensity of professional development, technological resources and support, principal and department chair turnover, computer lab type (separate lab versus in-classroom laptops), and the role of teachers' and students' prior experience with learner-centered instruction.

We used a grounded theory approach in the Glasserian tradition (Glaser, 1978), which makes use of all available data—including both qualitative and quantitative data—to explore themes across our cases. We systematically coded teacher interviews (which included questions about factors that enabled or hindered implementation), classroom observations, training observations, and communications with principals and department chairs. For several of the factors, we created quantifiable codes and conducted exploratory correlational analyses to examine relationships between the factors and levels of implementation. We also created matrices (Miles & Huberman, 1994) to examine patterns in qualitative data.

While it would be impossible to be certain that findings from a grounded theory analysis provide complete and accurate explanations of the case, our study design included several features that improve our confidence that our findings actually do fit the data. First, the randomized control trial design of the larger study—which allowed us to collect data about the same teacher using two different curricula—provided a useful framework for systematically sampling classroom observations and for exploring countervailing evidence (Miles and Huberman, 1994). Our study also benefitted from prolonged engagement in the field (Eisenhart and Howe, 1992)—including interacting face-to-face with each teacher at least seven times per year. Repetitive observations, interviews and conversations provided opportunities to collect missing data and confirm or improve the accuracy of previously collected data.

We dismissed many of our original hypotheses—due to lack of supporting evidence or the presence of contradictory evidence. However, we did find that, in general, there were certain conditions present across the study sample that seemed to enable implementation and other conditions that seemed to hinder implementation. At one level, our study schools appeared to be a fertile place in which to conduct our experiment. First, we found that the majority of teachers were generally positive—and in some cases excited—about the Cognitive Tutor curriculum. Although teachers reported that none of the principals or department chairs were closely monitoring implementation or providing teachers with opportunities for professional learning and collaboration to support their implementation, teachers did report that school administrators were generally encouraging teachers to implement the curriculum and were providing them with the resources to do so. We also found that teachers perceived their administrators to be supportive of the curriculum. Perhaps just as importantly, teachers did not report that they were faced with competing priorities and demands that may have hindered their implementation. Almost all of the teachers reported having all of the resources—such as materials and technology—that they needed to implement the curriculum.

On the other hand, we found that classrooms in our study were a challenging setting for several reasons. First, teachers and students had limited experience with learner-centered teaching and learning. Only four teachers reported that they had attempted to implement learner-centered practices prior to the study. Our observations in control classrooms documented that almost all teachers in the study tended to employ more traditional question-and-answer practices. Not surprisingly, when we controlled for teaching experience and year in study, we found that teachers' self-reported prior experience with learner-centered teaching practices was positively associated with their use of learner-centered practices in study classrooms. In particular, having experience with learner-centered practices prior to using the Cognitive Tutor curriculum was related to an increase of 0.64 points on the 6-point scale of implementation of learner-centered practices ($p=0.07$), holding constant overall teaching experience and a teacher's year in the study. We did not find statistically significant relationships between implementation levels and any of the other factors that we tested, including the teacher's year in the study (among those who took part in the study for at least two years).

Teachers also reported—and we often observed—that students in the majority of classrooms were reluctant to collaborate with other students. During collaborative time, we frequently observed students off task (for example, socializing, texting, or sleeping). Teachers' efforts to motivate or hold students accountable for engaging in the lesson often failed. Given that teachers were attempting to implement collaborative learning time more often in the treatment classrooms, they may have been inadvertently providing students with more opportunities to disengage. As such, the negative treatment effect was likely caused at least in part by poor implementation that resulted in low levels of engagement with mathematics for students in the treatment classroom.

The study classrooms were also a challenging context in that students tended to be "struggling math learners," as evidenced by their pre-test scores and our classroom observations. This may have greater importance in the treatment curriculum because it requires students to solve word problems. When students lacked prior knowledge, they often became stuck and stopped working on the task while they waited for the teacher to become available to answer their question. As illustrated in the example of a high-fidelity classroom in Appendix A, Carnegie Learning intends for students to ask each other for assistance in these situations, but this strategy seemed particularly problematic in a setting where the majority of students lacked prior knowledge and a culture of collaboration. As such, we frequently observed teachers in treatment classrooms calling a halt to collaborative learning time in order to walk students through the problems in a direct instruction format. We also found that the typical treatment lesson moved at a much slower pace than curriculum developers intended, usually covering only half of the planned activities. Meanwhile, in control classrooms, we often witnessed a more deliberate scaffolding of the knowledge students needed to solve practice problems (such as provision of a set of practice problems that slowly increased in difficulty) and more problems were covered in a single period.

A third challenge in the study was that most of the teachers (11 of 19) only taught the curriculum for one year. We designed the study with the intention of following teachers for multiple years so that we could understand whether and how quality of implementation changes over time. However, through a combination of teacher and school turnover within the study, our data set only included data for 8 teachers implementing the curriculum for a second year and, among those, 3 teachers implementing the curriculum for a third year. Therefore, the overall low levels of implementation might be explained by the fact that most teachers were new to the curriculum. Nevertheless, data from the teachers who implemented the treatment curriculum for a second and third year suggested that their implementation did not improve over time. In fact, the overall implementation scores of four teachers (of the eight total teachers who were in the study for at least two years) were slightly but non-significantly lower in their second year of implementation than their first.

A fourth challenge was that teachers did not participate in ongoing, job-embedded professional development to support their implementation. Most teachers did participate in three days of training provided by Carnegie Learning prior to the start of their first year using the curriculum. Carnegie Learning also provided a consultant who was available to visit teachers in their schools and provide coaching and feedback. Teachers reported that while this person did "check in" on them once and answered some simple questions, the support did not substantially affect their instruction. On two unplanned occasions we had the opportunity to observe the consultant's visit and interactions with the teacher. In both cases, the consultant asked the teachers if they had any questions at the end of the period as students transitioned in and out of the classroom and the teachers responded that they did not have questions. This was not surprising to the observers given that there was not a time and space for teachers to initiate a conversation lasting more than a minute or two. None of the schools had school-based math coaches, teacher leaders, department chairs, or other school leaders that supported teachers' general professional growth. Nor did teachers have common planning times and or a school culture that facilitated teacher collaboration. As such, the teachers did not engage in the types of ongoing, job-embedded professional development that characterizes high-quality professional development. Some teachers did attend more or less of the professional development that was offered for the curriculum, but this variation was not significantly correlated with implementation measures.

Discussion

Program adopters need research-based evidence not only about which curricula work, but also about the conditions under which they do or do not work. Our findings suggest that poor implementation of the instructional practices the materials and software were designed to support may have played a substantial role in the observed negative effect of the Cognitive Tutor Geometry curriculum. Despite scaffolding provided by the curriculum's teacher materials, the vast majority of participating teachers implemented learner-centered instructional practices at low levels. Although we detect only marginally significant relationships between implementation composites and student achievement, this may be due in part to the fact that there were few teachers with highly faithful implementation, particularly in the realm of learner-centered practices and student participation. Nevertheless, our qualitative analyses provide rich and detailed accounts of how poor implementation may have led to less rigorous learning experiences for students. These findings confirm a large body of research documenting that implementation matters (McLaughlin, 1991; Odden, 1991).

Based on detailed observations, it seems that teachers struggled to implement the student-centered practices prescribed by the curriculum. This difficulty existed despite detailed training and materials as well as access to a technical assistance provider and online support. While teachers had positive attitudes about the curriculum, they did not have the prior knowledge, curriculum experience, or ongoing job-embedded professional support that might have helped them to implement the student-centered practices with students who lacked prior knowledge and willingness to collaborate with other students. These findings also support prior research documenting challenges related to implementing learner-centered practices (e.g., Desimone, Smith, Ueno, & Baker, 2005). Our findings also extend this research by suggesting that curriculum materials by themselves cannot overcome these challenges. That is, curricula and software cannot make learning experiences for students "teacher proof". This finding is particularly noteworthy given that some adopters—despite cautions from the developer—view the software component of the Cognitive Tutor curriculum as an easy way to provide students with individualized tutoring without having to train teachers how to implement difficult instructional practices.

These implementation findings are important because they offer insights to policymakers trying to determine whether and how our study's overall finding of a negative treatment effect of the Cognitive Tutor geometry curriculum might apply to their situation. First, these findings suggest that policymakers in a similar context—with similar types of teachers and students—should think twice before adopting the curriculum. If they do want to adopt it, they should consider providing intensive professional development and support to assist teachers in achieving high implementation. Furthermore, they should understand that achieving high implementation could take years, and they should therefore only implement it in contexts where teachers are likely to use it repeatedly (as opposed to situations with high teacher turnover). Finally, they should consider implementing it in contexts where students are accustomed to working in a student-centered classroom, where they might already have skills to collaborate with others and seek answers to their own questions.

Our study also leaves a number of questions unanswered, which we suggest should be addressed by further research. For example, how does quality of implementation of the Cognitive Tutor geometry curriculum vary across various contexts? Could we expect implementation to be better in classrooms with students of higher ability or socio-economic status? Could we expect it to be better in schools with greater use of student-centered learning practices? Can quality of implementation be improved through professional development and support? If so, what kind of professional development and support is needed? How does quality of implementation change as teachers have more experience implementing the curriculum?

Future impact evaluations (in general, not just those related to the Cognitive Tutor geometry curriculum) should also address these types of implementation questions. Without a detailed examination of how implementation matters, such studies risk providing overly simplistic interpretations of causal outcome results, and potentially flawed recommendations on whether interventions should be widely adopted (Honig, 2006). Detailed implementation studies can provide a nuanced understanding of how various factors relate to implementation and inform policymakers' decisions regarding when conditions are optimal for adopting a curriculum. They can also provide insights about the types of curriculum modification or professional development that may be needed to support teachers' efforts to implement the curriculum.

Notes

[1] Statistical models, estimated coefficients, and standard errors are reported in Author et al. (2010).

[2] Although prior research has found that observational ratings tend to remain stable across days (e.g., NICHD ECCRN, 2005) and many studies only use one observation, we wanted to explore whether implementation improved over time as teachers began working with a new curriculum. When we discovered this was not the case, we decided to average the scores, which is consistent with approaches taken by other peer-reviewed studies (for example see Raver, Jones, Li-Grining, Metzger, Champion & Sardin, 2008).

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Appendix A: Summary Example of a High Implementing Cognitive Tutor Geometry Classroom

Lesson Introduction

After spending seven minutes reviewing the homework, the teacher introduced the Cognitive Tutor lesson on "area of a triangle" by having students turn to page 21 of their workbooks and reading the scenario at the top of the page, "In sailboat races, one of the typical shapes of a racing course is triangular. The course path is identified by buoys called marks. When the course is a triangle, the marks are located at the vertices of the triangle." The teacher helped students make connections to their life experiences by asking, "Where have you seen sailboats?" Students called out responses such as, "At the marina" and "We saw them in Old Town." She reviewed vocabulary like "racing course" and "buoys" and made connections to students' prior knowledge about vertices.

The teacher also made connections to future material by saying, "The wind has a lot to do with where the boat goes. We will learn more about wind when we study vectors." She made more connections to prior knowledge by telling students to recall what they learned about parallelograms and to apply that knowledge to solving for the measures of a triangle. To help students solve for the area, she reminded them of an activity they had undertaken in the first week of school. She prepared students to address potential problems by telling them that they would need to know the formula for the area of a triangle, reminding them of the formula and how to identify the height. She further reminded them that height "does not always go up and down," and showed them an example of a triangle for which the height was horizontal. Finally, she asked students to turn to a question on page 26 and to realize that when the text asked them for the length of the course, it was really asking them to solve for the perimeter.

Activity and Materials

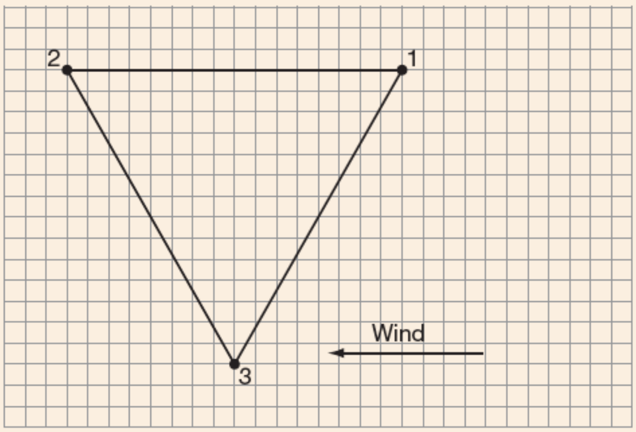
The students were already seated in clusters of four desks with their regularly assigned group members. The teacher told students to work with their group members to answer questions on pages 21 and 22 of their workbooks, which consisted of nine open-ended questions. Figure A1 provides a truncated version of the first few questions of the assignment.

Figure A1. First page of assignment in high implementing Cognitive Tutor Geometry classroom

SCENARIO In sailboat races, one of the typical shapes of a racing course is triangular. The course path is identified by buoys called marks. When the course is a triangle, the marks are located at the vertices of the triangle.

Problem 1 The Race Course

A sample course with the marks numbered is shown on the grid below. Each square on the grid represents a square that is one tenth of a kilometer long and one tenth of a kilometer wide.



A. How many grid squares in a row create an area that is one kilometer long and one tenth of a kilometer wide? Use a complete sentence in your answer.

B. How many grid squares are in an area that is one kilometer long and one kilometer wide? Use a complete sentence in your answer.

C. Estimate the area enclosed by the course. Use a complete sentence in your answer.

Teacher Practice

As the students began working in their groups, the teacher encouraged them to be responsible for their own learning by carefully re-reading the problem, using their glossary, and consulting with team members before asking the teacher for help. As she circled the room, she almost always responded to students' questions by prompting them to ask another group member. In one instance, she re-directed the question herself. As a result, she typically only spent a few seconds responding to any one student. When she thought a question warranted further explanation, she stopped the entire class to provide an explanation at the board.

The teacher frequently encouraged students to be responsible to their groups. For example, she told one student that he was working too far ahead and that he should wait for his team members. She also reprimanded a student who suggested to his group that they divide up the problems, telling him, "You know we don't do that!" She also announced to the class that it was more important to have the same answer than to have the right answer.

Student Engagement

The students spent 30 minutes working in groups. Although there were many examples of students asking the teacher for help, the observers witnessed multiple examples within each group of students explaining how to solve the problem to their group members. For example, one student showed another how to find the length of a side by counting along the grid line. In another group, a student asked a group member, "What did you get for question five?" After her group member responded, she asked, "Wait, how did you get that?" and her group member explained her process for arriving at the solution.

Although there were several instances of students socializing during group work time, they often continued to work while socializing or only remained off task for a short period of time. All students were engaged for the vast majority of the period.

Closure

The teacher brought closure to the lesson by having each group present its answers to two of the workbook problems. She gave them 10 minutes to write their answers on the board before the presentations began and encouraged students to be responsible for each other's learning by telling the rest of the group members to, "Pay attention to what your group member is writing and let them know if you don't like something they've written so that they have time to correct it." She reiterated this by walking over to a group that was not paying attention, telling them to look at what their group member was writing on the board, and instructing them to make sure it was right.

She prefaced the actual presentations by reminding students that they were responsible for paying attention and for understanding how to solve all of the problems. She said they should have all the right answers on their paper by the end of the period, but that they should refrain from copying down answers until the problem had been discussed and they were certain that the answer on the board was correct.

She required groups to assign a presenter who had not presented before, but reiterated that the group was responsible for making sure their presenter understood the problem and presented it correctly. When presenters made mistakes or could not answer the teachers' probing questions, she re-directed the questions to the group and then to the entire class. She also allowed time for the rest of the class to ask the presenters questions. By the end of class, the students had reviewed all of the problems as a class—allowing the teacher to assess and reinforce their understanding of the material.

Appendix B: Summary Example of a Typical Treatment Cognitive Tutor Geometry Classroom in BCPS

Lesson Introduction

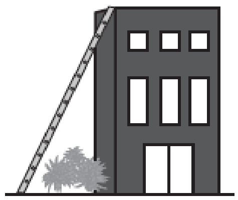
After spending 12 minutes on a drill and reviewing it as a class, the teacher introduced the lesson by having the students turn to page 157 of their workbooks and asking a student to read the scenario out loud. As the student read, the teacher addressed three students who had not come to class prepared with their workbooks. The class waited and began to socialize as the teacher took four minutes to access the Carnegie Learning website to print extra copies of the workbook pages for the students without textbooks. No other introduction was provided before the teacher assigned the activity.

Activity and Materials

After a few moments spent regaining the students' attention, the teacher explained that they would be working on pages 157 and 158 (see truncated version of page 157 in Figure B1) and that the assignment should be completed by the end of the class period. She assigned new groups, explaining to the students that they had not worked well together in the previous groups and that the new groups were designed to provide better matches. The assigned pages consisted of a scenario and six open-ended questions, similar to the assignment in Appendix A.

Figure B1. First page of assignment in typical treatment Cognitive Tutor Geometry classroom

SCENARIO A company has been hired to install a satellite dish on the roof of a building. The building's owner has given specific instructions that the plants and shrubs around the base of the building are not to be disturbed in any way. One of the workers must choose the ladder that will be long enough to reach the roof of the building while not disturbing the plants. A diagram of this situation is shown below.



Problem 1 Coming Up Short

A. On the figure above, draw the triangle that is formed by the ladder, the building, and the ground. Label the vertices of the triangle.

B. Classify the angles in your triangle. Use a complete sentence in your answer.

C. Without measuring, identify the longest side of the triangle. How do you know that this side is the longest side? Use complete sentences to explain your reasoning.

D. Suppose that you know that the building is 16 feet tall and that the foot of the ladder must be placed 12 feet from the building. What do you know about the length of the ladder? Explain your reasoning. Use complete sentences in your answer.

Teacher Practice

The teacher circulated among the groups, fielding students' questions. She repeatedly encouraged students to pose questions to each other and explain answers to group members when they figured them out. For example, she responded to the first three questions she received by saying, "Ask a group member." She further discouraged students from relying on her for answers by providing each group with two question cards. Each group had to turn in a question card to ask the teacher a question, and therefore was limited to two questions per class. The teacher began accepting question cards and sat with each group for several minutes helping them to work through the problems. She also approached groups when she noticed they were off task to encourage them to refocus on their work.

Student Engagement

At the beginning of the group work activity, students took approximately 10 minutes to physically relocate themselves into their groups, and once there, many socialized or simply stared into space until they were prompted to engage by the teacher. After another four minutes, most of the students were actively doing the work, but were working independently rather than with peers.

For each group, the observer noted only one or two exchanges in which students were discussing mathematics. Though the teacher had prompted students to pose questions to each other, they were not responding accordingly. For example, when a student called the teacher over with a question, the teacher asked the other members of the group whether anyone had determined the answer. One student replied with the correct answer. The teacher acknowledged it was the right answer, but said, "Explain how you got that to your group, don't just give the answer." However, when the teacher walked away, the group began to socialize instead.

The observer noted additional instances of weak student engagement. For example, after 10 minutes of group work, two members of one group had not written anything on their papers. The other two members of the group had written answers to three problems, but were staring into space as the observer walked by them. The observer noted that the latter two students re-engaged four minutes later when they began discussing their answers to the second problem. In another group, two boys were sitting close together; one was quickly answering many of the problems while the other directly copied the answers onto his own paper.

Closure

The class ended when the bell rang while students were still arranged in groups. It appeared that some students had finished the assignment but most had not. The teacher announced as students exited that any unfinished work should be completed for homework.

Appendix C: Summary Example of a Typical Control Geometry Classroom in BCPS

Lesson Introduction

After spending 25 minutes at the front of the room leading students through a check of homework questions and through the steps to solve a warm-up drill, the teacher began the day's lesson by writing the on a transparency projected onto the board and telling students to take notes. She wrote the objective, "Students will be able to name similar parts of congruent figures and find the similarity ratio of similar figures" and then drew two congruent triangles and explained how to label them. After each step, she waited for students to copy the material. She also explained how to determine which sides were congruent and then quizzed the class regarding particular sets of sides. For example, she asked, "Can you say that CA is congruent to FD?" Students responded "yes" or "no". Then she drew two sets of trapezoids, asked students to define trapezoids, and used a question-and-answer technique to prompt students to name corresponding angles and sides.

Next, the teacher introduced the concept of similar figures. She asked if they had learned about similar figures before, but no one answered this question. She wrote the definition of similar figures on the board—"The angles are congruent and sides are proportional"—and asked where they had seen the term 'proportional' before. When no one answered, she told them they had seen it in pre-algebra and tried to jog their memories by listing the names of pre-algebra teachers at the school.

The teacher then defined the similarity ratio and demonstrated how to solve for it. She used a question-and-answer technique to walk the class through several examples, which included the following exchange:

T: What side corresponds with y?

S: 6

T: Right, so I set my similarity ratio equal to y over 6. Make sure that if your similarity ratio is for big triangle over small triangle that you are setting your new fraction so that the big triangle side is over the small triangle side. So, 2 over 1 equals what?

S: y over 6

T: Right and then you cross multiply. So, you get y = 12.

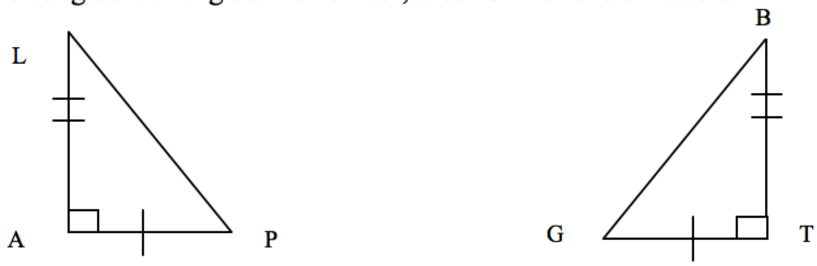
The teacher attempted to get the students to lead the next problem by asking for someone to set up the similarity ratio, but no one answered. She called on a student who provided the wrong answer; the teacher then led the class in solving the problem and the following problem.

Activity and Materials

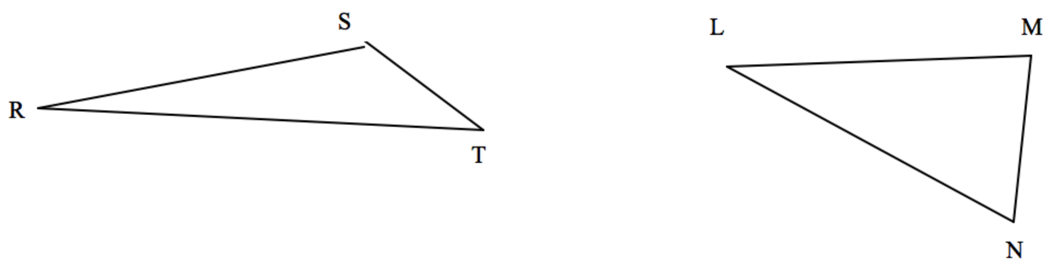
After the 30-minute lecture, the teacher distributed a ditto that she had created (see Figure C1) with 21 practice problems related to similar parts of congruent figures and similarity ratios. She told students that they could opt to work with a neighbor.

Figure C1. First page of assignment in typical control geometry classroom

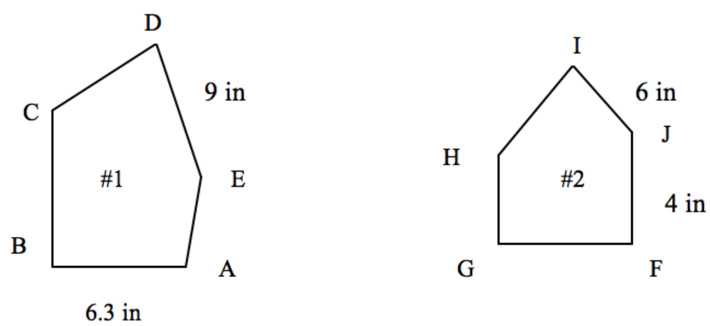
1. Name the congruent triangles. Remember, order of the letters matters!



2. If $\triangle$ RST $\cong$ LMN, name all three pairs of congruent angles and all three pairs of congruent sides.



3. Use the information in the pictures below to answer the following questions:



ABCDE ~ FGHIJ

a) Find the similarity ration of pentagon #1 to pentagon #2.
b) If AB= 6.3 inches, find FG.
c) If JF= 4 inches, find EA.
d) If m ∠ABC=90, what is m∠FGH?
e) If m∠D=84 degrees, name another angle that is 84 degrees.

Teacher Practice

During the first part of the practice problems, the teacher responded to raised hands. She typically sat with each student for several minutes, walking the student through the problem step-by-step. The following exchange was typical:

T: You need to name this triangle, what do you want to name it?

S: [Responds by labeling the triangle vertices A, B, and C]

T: Good. Now you need to name the second triangle, but order matters this time. If you started with this [pointing to angle of first triangle], which angle do you need to start with on the second triangle?

S: B.

T: Right, and which angle should you name next?

After the teacher spent several minutes explaining the first problem to three different students, she pulled the class back together as a group, and used a transparency to walk the entire class step-by-step through the next three problems. Then she instructed students to finish the rest of the practice problems on their own, and she continued circulating through the room.

Student Engagement

During the lesson introduction, the majority of students were following along and actively taking notes. However, two students did not have a notebook out and a third student was sleeping with his head on the desk. There were only two or three students who voluntarily responded to questions when the teacher posed them to the class.

During seatwork, the majority of the students remained seated individually. Two girls moved their desks closer together and socialized quietly. Two boys moved their desks together but appeared to continue working individually. At first, the room was quiet. A couple of minutes after starting the assignment, the observer counted six hands in the air, indicating these students were waiting for the teacher to provide assistance. After a few minutes, these and several other students began socializing as they waited for the teacher. When the teacher called them back together as a class, the majority of students copied the answers as the teacher walked through the problems. When they returned to individual work, the majority of students continued to work on the problems, although some appeared to be working more diligently than others. Most student interactions were social in nature, including a lot of bantering and teasing. In a few instances, the observer noted one student asking another for the answer to a particular problem, as in, “What did you get for number 7?” But in these instances, students did not discuss how they had arrived at their answers.

Closure

The class ended when the bell rang. Approximately 10 minutes before the end of class, several students had finished the assignment, and the teacher suggested they start their homework, but they socialized instead.