Investigating Effects of Embedding Collaboration in an Intelligent Tutoring System for Elementary School Students

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Abstract: Intelligent Tutoring Systems (ITSs) are beneficial for individual students learning in several domains, including mathematics where they have been used to support both secondary and elementary students. Collaborative learning may be beneficial to include in ITSs, particularly for conceptual knowledge. There is little work on collaborative ITSs, and it has mostly focused on older students. We aim to extend this work to elementary school students, by extending an ITS for fractions so it supports collaborative learning. We also build upon our previous work to further investigate the complementary strengths of collaborative and individual learning. In our study, 189 elementary school students worked with a conceptual or a procedural fractions ITS, and either individually or collaboratively. Students in both ITS conditions learned, but there were no differences in learning between individual and collaboration. However, the students working collaboratively spent less time on the tutor, indicating potential benefits of collaborative learning on efficiency in this setting.

Keywords: collaborative learning, intelligent tutoring systems, primary school

Introduction

Intelligent Tutoring Systems (ITSs) have been very successful in supporting students' learning as they work individually to solve problems (VanLehn, 2011). Although this individual work has been shown to be beneficial, there may be additional benefits from students being able to work collaboratively, especially when they are acquiring conceptual knowledge (Mullins, Rummel, & Spada, 2011). Previous research has shown that integrating collaboration into an ITS environment can be conducive for learning (Walker, Rummel, & Koedinger, 2009). But most of this work has been done with older students and has not been extended to elementary school students where collaboration is expected to be more challenging. We aim to investigate if the benefits seen with older students can apply to elementary school students and how best to utilize collaboration and individual learning within an ITS to support students.

Although ITSs have been shown to be beneficial to students in many domains (Murray, 2003), they have been shown to be particularly successful with mathematics (Ritter, Anderson, Koedinger, & Corbett, 2007). For elementary school students, fractions are challenging (Moss, 2005), but the learning of fractions can be successfully supported through the use of an ITS, showing that ITSs can be beneficial for young learners (Rau, Aleven, & Rummel, 2012). ITSs are beneficial to students by providing them with cognitive support as they solve a problem (VanLehn, 2011). ITSs provide step-by-step guidance for students both through the use of immediate feedback on steps and through on demand hints. That is, students will know right away when an error occurs and they can decide to request help from the system to figure out how to do any problem-solving step correctly. ITSs also track individual students' knowledge growth, which enables them to implement a cognitive mastery approach with individualized problem selection. ITSs often focus on helping students acquire problem-solving skills, and by integrating collaboration, we may be able to support students in explaining their reasoning, as is specified in the United States common core standards (Common Core State Standard Initiatives, 2015).

Collaboration is often beneficial for learning (Slavin, 1989; Lou, Abrami, & d'Apollonia, 2001) and is a way to get students to express their reasoning (Hausmann, Chi, & Roy, 2004). Collaborative problem solving may help students develop a deeper conceptual understanding (Teasley, 1995) through mechanisms such as co-construction and explanation-giving (Hausmann, Chi, & Roy, 2004; Chi & Wylie, 2014). Through these mechanisms, collaborative learning may be beneficial as an addition to standard ITS technology, especially for conceptual knowledge where students often need to develop a deeper understanding of concepts in the domain (Mullins et al., 2011).

Although most prior research on ITSs has focused on students working individually, there has been some work combining ITSs and collaboration with high school students (Baghaei, Mitrovic, & Irwin, 2007; Walker et al., 2009; Diziol, Walker, Rummel, & Koedinger, 2010). Walker, Rummel, and Koedinger (2009) found that students working with a tutor that had been redesigned to support peer tutoring (i.e., the tutoring system provided support to the student in the role of the peer tutor) achieved learning gains at least equivalent to those working individually, demonstrating that collaboration can be successfully combined with ITSs. However, much of this work has been done with secondary and college students rather than elementary school students. For elementary school students, learning collaboratively may be challenging, especially in STEM domains such as mathematics (Mercer & Sams, 2006). Elementary school students often do not have fully developed social skills, making collaborative activities more challenging. Also, elementary school students may not have developed the vocabulary to discuss complex math concepts and relations. Despite these challenges, collaboration may still be effective for elementary school students by allowing them to make their thinking explicit and to practice their ability to talk about mathematics (Chi & Wylie, 2014). Even outside of ITSs, few studies have investigated whether computer supported collaborative learning (CSCL) can have a positive impact on learning with elementary school students. The studies that have been conducted in this area have either compared the use of a CSCL setting to face-to-face collaborative learning (i.e., not supported by computers) or have focused on technology interventions that mix individual and collaborative learning tasks without comparing learning collaboratively to learning individually as we propose to do (Chen & Looi, 2013; Lazakidou & Retalis, 2010; Tsuei, 2011). This research has shown positive impacts of young children working in small groups and with computers that can be extended to the use of ITSs.

In addition, collaborative and individual learning may have different strengths. For example, individual and collaborative learning activities may be better for acquiring different types of knowledge, such as conceptual and procedural knowledge (Mullins et al., 2011). Conceptual knowledge is the implicit and explicit understanding of the principles in a domain and how they are interrelated (Rittle-Johnson, Siegler, & Alibali, 2001) and may be better acquired through collaboration (Teasley, 1995). Procedural knowledge is the ability to be able to perform the steps and actions in sequence to solve a problem (Rittle-Johnson, Siegler, & Alibali, 2001) and may be better acquired through individual work with the opportunity of more practice. Understanding the relative strengths of individual and collaborative learning, which we focus on in this paper, may ultimately help in designing instructional conditions that effectively combine individual and collaborative learning.

In a previous study with elementary school students (Olsen, Belenky, Aleven, & Rummel, 2014a), we did not find differences in learning gains between students working collaboratively or individually for either conceptual or procedural knowledge. However there were several weaknesses in the study that we are addressing with the current study. In the previous study, the procedural tasks may have been too difficult for the students. Also, the total instruction time was only 45 minutes, which may not have been enough for differences in learning gains to emerge. The current study took place in a more realistic classroom setting (the previous study was a pull-out study), allowing the students to speak more freely and to work with the tutor across multiple sessions. The study involved 189 students and ran over five class periods to provide time for multiple units to be completed. To test our *hypotheses* that a collaborative ITS can effectively support young learners, and that collaborative and individual learning have different strengths for conceptual and procedural knowledge, we used two separate 2-condition between-subjects designs. Each compared a collaborative and an individual learning conditions, one with a conceptually-oriented set of tutor problems, and one with a procedurally-oriented set of tutor problems. This design allows us to compare between individual and collaborative learning within both conceptually-oriented and procedurally-oriented tutors. The design is not a true 2x2 design. The conceptual and procedural tutors cannot be directly compared because they support different learning goals.

Methods

Before we present the study in more detail, we describe our ITS designed to support fractions learning.

Tutor design

Informed by prior work on the Fractions Tutor (Rau et al., 2012) and our previous collaborative tutors for equivalent fractions (Olsen et al., 2014a), we developed a new ITS for a range of fractions units. To compare students working collaboratively to students working individually, we built two parallel versions of the tutors for use in our study, one for collaborative learning and one for individual learning. The ITS versions were built with the Cognitive Tutoring Authoring Tools (CTAT), extended to support collaborative tutors (Olsen et al., 2014b). For both collaborative and individual learning, we created two sets of tutor units, focused on either procedural knowledge or conceptual knowledge. For both sets, the units covered were naming, making, equivalent, least common denominator, comparing, adding, and subtracting fractions. For each unit, there were eight problems. All of the problems within a unit were of the same type and focused on the same procedure or concept. The problems were divided between graphical representations with two problems focusing on circles, two problems focusing on rectangles, and four problems focusing on number lines. Although the conceptually-oriented and procedurally-oriented tutors covered the same units, the materials were fundamentally

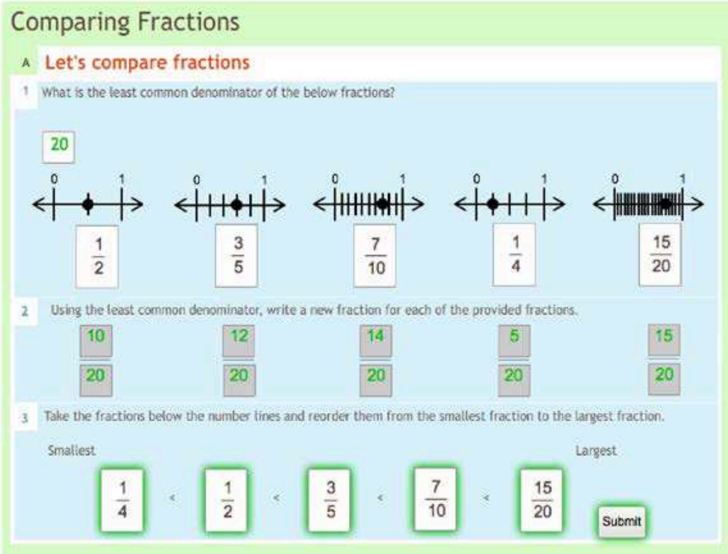

Figure 1. An example of an individual procedural problem for comparing fractions. The students go through the steps of converting fractions as a general mathematical procedure for solving this type of problem.

different to match different learning goals. For the procedural problem set, the students went through the steps needed to solve the problem. For example, for the comparing fractions unit, students would first find the least common denominator for the fractions they were trying to compare (see Figure 1) and then convert all of the fractions using this common denominator. Once they had completed this process, they were asked to put the fractions in order, from smallest to largest. For the conceptual problem set, the students were asked to fill in answers to see a pattern in the fractions, and then to fill in the blank for sentences to generalize the patterns to fractions concepts. For example, for the comparing fractions unit, the students were asked to mark if fractions were larger or smaller than one another. These fractions consisted of one where the denominators were the same, one where the numerators are the same, and one that is mixed (see Figure 2). The students were then guided to understand that when numerators are the same, then the fraction with the smaller denominator is larger, and when the denominators are the same then the fraction with the larger numerator is larger. These fill in the blanks were reworded for every other problem so students could not just memorize the slot that each answer should go into.

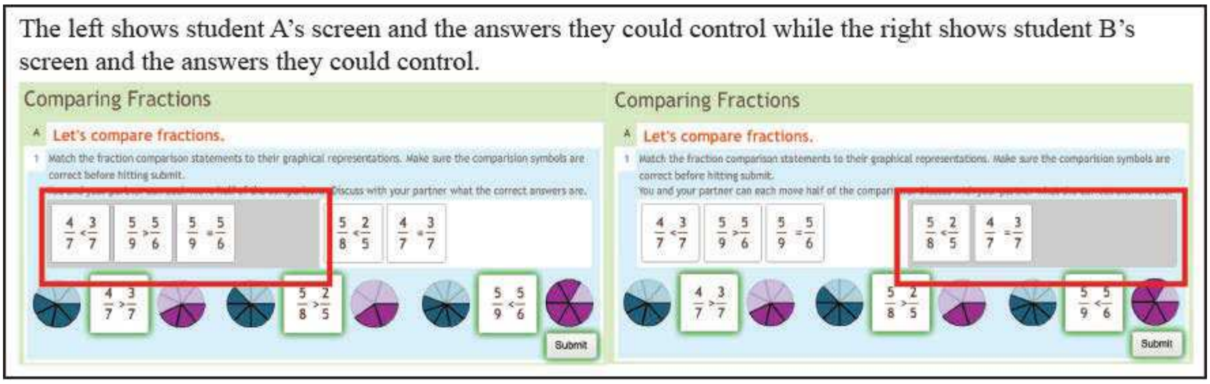

Figure 2. An example of a collaborative conceptual problem for comparing fractions. In panel A, each student is responsible for half the answers while in panel B the students share the responsibility for the questions.

In addition to the cognitive support normally provided by an ITS (step-level guidance for problem solving) that is used in both the individual and collaborative tutors, the collaborative tutors are also supported with embedded collaborative scripts for each tutor problem to provide social support for students (Kollar, Fischer, & Hesse, 2006). The collaborative tutors support synchronous, networked collaboration, in which collaborating students sit at their own computer and have a shared (though differentiated) view of the problem state and different actions/resources available to them. The students sat next to each other and communicated through speech. The embedded scripts supported collaboration through a distribution of responsibility to create accountability and interdependence (Slavin, 1989). The students were responsible for different parts of the problem (see Figure 2).

Often in the problem, each student had some action that only they could take for the step to be completed. This supported both students in needing to contribute. In Figure 2, each student has a set of the compared fractions. The students cannot fill in all three of the answers by themselves because they do not have access to all of the correct answers. They need to work together with their partner to fill in all of the blanks and submit the problem. This distributes the responsibility for each of the steps across both students. In addition, some steps created interdependence between the students. An example is for equivalent fractions that if one student entered a numerator, this would influence what the correct denominator would be for their partner. The embedded scripts provided support for the collaboration to be directly integrated into the ITS. Besides the embedded collaboration script, all collaborative and individual tutors were designed to be identical to allow for a comparison. During the time with the ITS, students who were collaborating sat next to each other but worked on different computers. They communicated through speech, which was recorded.

Experimental design and procedure

We conducted a study with 189 4th and 5th grade students from two schools across two school districts. The students came from a total of nine classrooms and five teachers. The experiment took place during the students' regular class periods. All students worked with the fractions ITS described above, either on conceptually-oriented tasks only or on procedurally-oriented tasks only, and working either collaboratively all the way through or individually all the way through. Thus, we had 4 conditions, which, as discussed above, we analyze as two separate 2-conditions designs. Students were assigned to individual and collaborative conditions based on class for a quasi-experimental design. This random assignment based on class was done to limit the disruption to the class. There were five classes that were assigned to work collaboratively and four classes that were assigned to work individually. Within each class, teachers paired their students based on students who would work well together and had similar math abilities. These pairs were then randomly assigned to work on the procedurally-oriented or the conceptually-oriented problem sets. Within the class there was an even split between students working on conceptually-oriented problems and students working on procedurally-oriented problems.

During the study, if a student's partner was absent in the collaborative conditions, the student would be paired with another student working on their same type of problem set for the remainder of the experiment. If there were two students that needed partners who had worked together before, they were paired together. If there were an odd number of students who needed a partner, then one student would work individually for the day. The teacher informed student pairings with a new partner when there was more than one option. When students started with a different partner from the day before, they would begin on the problem set at the place of the student that was less far in the problem sets.

The study ran across five days for each class where each day the students had 45 minutes to work with the tutor. On the first day, the students took the pretest individually. When they completed the pretest, they moved onto a tutorial that gave some instruction on how to interact with the tutor; otherwise, this was done on the second day. The students then worked with the tutor for the next three days in their condition. On the fifth day, the students took a posttest individually.

Test items

We assessed students' knowledge at two different times using two equivalent test forms in counterbalanced fashion. The tests targeted both conceptual and procedural knowledge types for all conditions. Each test had 20 questions, 10 procedural and 10 conceptual where six were isomorphic with the main six fractions units and four were near transfer targeting the four upper level fractions units. For each question on the test, the students were able to get a point for each step completed correctly. On the tests there were 23 possible conceptual test points and 68 procedural test points. Because of the discrepancy in points for the different types of knowledge, for both conceptual and procedural test scores, the percentages were used for all analyses.

Results

Due to absenteeism during the study, only 146 of the 189 students were used for the analysis. Students were excluded if they missed either the pretest or posttest. They were also excluded if they missed more than 1 day of working with the tutor. In the collaborative condition, students were excluded if they had more than a total of two partners during the tutors. There was no significant difference between conditions with respect to the number of students excluded, $F(3, 185) = 0.72, p = .54$. There was also no significant difference between conditions on the pretest score for either the conceptual test items, $F(3, 142) = 0.49, p = .69$, or for the procedural test items, $F(3, 142) = 0.68, p = .57$.

As discussed, we used a separate 2-condition between-subjects design to compare an individual and a collaborative learning condition for conceptually-oriented and procedurally-oriented tutor problem sets. For the analysis, the data was thus treated as two separate data sets within which students working collaboratively or individually could be compared. Out of the 146 students used in the analysis, 70 students worked with the procedurally-oriented ITS, and 76 students worked with the conceptually-oriented ITS.

Pre/posttest learning gains

To investigate whether students learned using our tutors, and if there was a difference in learning between the students working collaboratively and students working individually within the two tutor problem sets, we used a multilevel approach to take into account the repeated measures of the pretest and posttest and differences between teachers. Within this analysis, we treated all students as individuals. We conducted a hierarchical linear model (HLM) with student at the first level and teacher at the second level. At level 1, we modeled the pretest and posttest scores, and at level 2, we accounted for random differences that could be attributed to the teacher. We did not include dyads as a level because of the added complexity of some students working with no partner (i.e. individuals), some students having one partner, and some students having two partners because of absenteeism. We are aware of non-independence issues such as common fate and reciprocal influence that may impact our results (Cress, 2008). We measured the effect size with Pearson's correlation coefficient (*r*) where 0.1 is a small effect size, 0.3 is a medium effect size, and 0.5 is a large effect size.

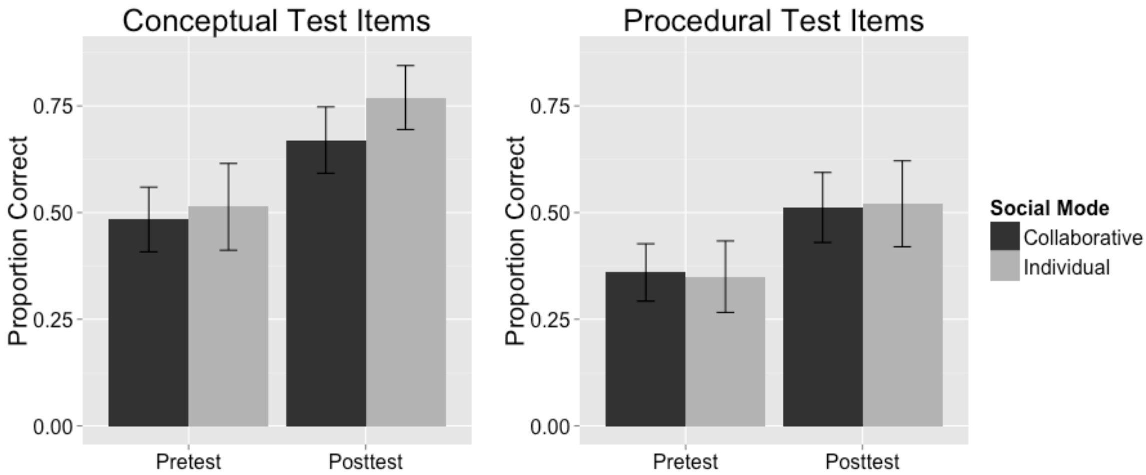

Figure 3. Learning gains on the conceptually-oriented tutors. Conceptual test items on the left and procedural test items on the right. Collaborative students are black and individual students are light gray.

First, we analyzed data from students who worked with the *conceptually-oriented tutors*. We tested whether there were statistically significant pre/post learning gains and we compared the learning gains between students working individually and students working collaboratively. We did so separately (with separate HLMs) for gains on the conceptual test items and gains on procedural test items. For the conceptual test items, a significant effect between pre and posttests was found with posttest having a higher score, $t(74) = -9.29$, $p < .001$, $r = .73$, while no significant effect for individual/collaborative learning, $t(70) = -1.25$, $p = .22$, $r = .15$, nor interaction, $t(74) = 1.47$, $p = .15$, $r = .17$, was found (see Figure 3). For the procedural test items, a significant effect between pre and posttests was found with posttest having a higher score, $t(74) = -6.80$, $p < .001$, $r = .62$, while no significant effect for individual/collaborative learning, $t(70) = 0.35$, $p = .72$, $r = .04$, nor interaction, $t(74) = 0.39$, $p = .70$, $r = .05$, was found (see Figure 3). Thus, although there was learning from pretest to posttest on both conceptual and procedural test items, there was no difference in learning between students working individually and students working collaboratively. To investigate whether there was a difference in the time it took students to complete the posttest, we ran a t-test. No significant difference was found for the time it took students to complete the posttest between the students working individually and students working collaboratively, $t(74) = -1.16$, $p = .25$.

Second, we analyzed data from students who worked with the *procedurally-oriented tutors*. We tested whether there were statistically significant pre/post learning gains and we compared the learning gains between students working individually and collaboratively. We did so separately (with separate HLMs) for gains on the conceptual test items and gains on procedural test items. For the conceptual test items, a significant effect between pre and posttests was found with posttest having a higher score, $t(68) = -4.49$, $p < .001$, $r = .48$, while no significant effect for individual/collaborative learning, $t(64) = 0.68$, $p = .5$, $r = .08$, nor interaction, $t(68) = -0.56$, $p = .58$, $r = .07$, was found (see Figure 4). For the procedural test items, a significant effect between pre and posttests was found with posttest having a higher score, $t(68) = -8.40$, $p < .001$, $r = .71$, while no significant effect for individual/collaborative learning, $t(64) = 0.04$, $p = .97$, $r = .005$, nor interaction, $t(68) = -0.57$, $p = .57$, $r = .07$, was found (see Figure 4). Similar to what we found with the conceptually-oriented tutor, there was learning from pretest to posttest with the procedurally-oriented tutor, on both conceptual and procedural test items, but there was no difference in learning between students working individually and students working collaboratively. Also, no significant difference was found for the time it took students to complete the posttest between the students working individually and students working collaboratively, $t(68) = -0.49$, $p = .62$.

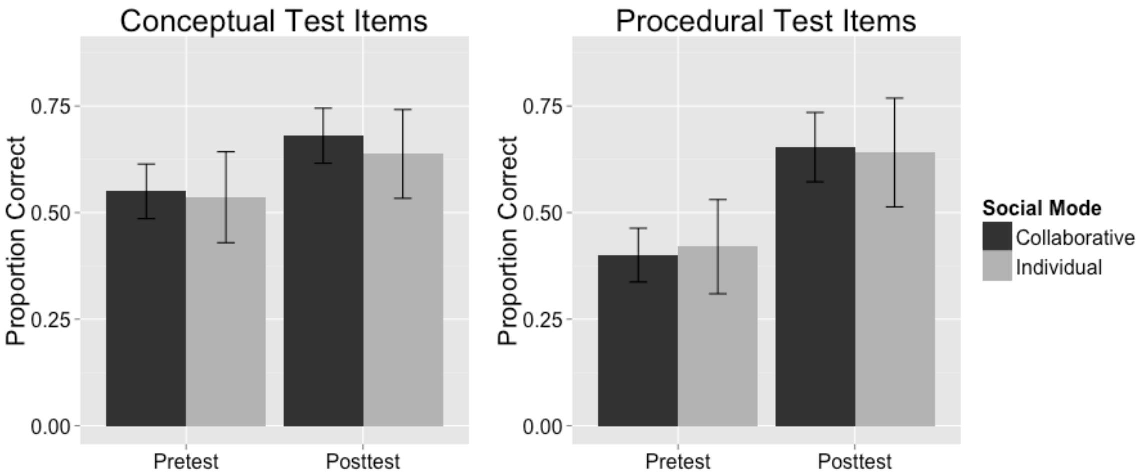

Figure 4. Learning gains on the procedurally-oriented tutors. Conceptual test items on the left and procedural test items on the right. Collaborative students are black and individual students are light gray.

Time on ITS

Table 1: Mean time and problems completed on the ITS for each condition and standard deviations

Tutor Materials	Social Mode	Time in Minutes: M (SD)	Problems Completed: M (SD)
Conceptually-oriented	Collaborative	73.32 (13.24)	44.08 (11.73)
	Individual	84.16 (18.11)	45.24 (14.50)
Procedurally-oriented	Collaborative	72.78 (13.34)	44.80 (10.29)
	Individual	84.11 (20.68)	45.30 (12.65)

For the study, ample time was given to students to work with the ITS with the expectation that all students would complete all of problems for the assigned units. Using two t-tests, we found no difference between students working individually or collaboratively in the number of problems completed for the conceptually-oriented tutors, $t(74) = -0.38$, $p = .7$, $r = .04$ or the procedurally-oriented tutors, $t(68) = -0.18$, $p = .86$, $r = .02$ (see Table 1). However, because the number of problems was fixed, students could work at their own pace and would finish the tutors at different times. Using two t-tests, there was a significant difference between students working individually/collaboratively on the time spent on the tutor for the conceptually-oriented tutors, $t(74) = -2.99$, $p < .01$, $r = .33$, and the procedurally-oriented tutors, $t(68) = -2.78$, $p < .01$, $r = .32$, where, surprisingly, students working collaboratively spent less time on the ITS (see Table 1). The students working collaboratively were able to complete the same number of problems as the students working individually but in less time.

Discussion and implications

The results of our study showed significant learning gains for students working collaboratively with both the procedurally-oriented and conceptually-oriented tutors. There was no difference in the learning gains of students working collaboratively versus students working individually. However, students working collaboratively completed the same number of tutor problems in less time on the tutor. These results confirm our hypothesis that young learners can be successfully supported in learning through the use of a collaborative ITS and indicate that a collaborative ITS is a viable option to use in the classroom.

The results did not support our hypothesis that students working on conceptually-oriented tasks would benefit more from collaboration and students working on procedurally-oriented tasks would benefit more from working individually. These results are consistent with the findings from our previous work where we also found no difference in learning gains (Olsen et al., 2014a). However, learning with an ITS individually has been shown to be very successful, especially within mathematics (Ritter et al., 2007; Rau et al., 2012), and it may be very difficult to design an intervention that can be added to an ITS to increase learning above what can be achieved working individually. Collaboration adds an extra layer of complexity that might be expected to inhibit the learning process, even within an ITS. Yet both in our previous work and in the current study, we found evidence that collaborative learning with an ITS can be more efficient than learning individually with an ITS. In our prior study, students had the same learning gains when working collaboratively as when working individually, but they had practice with fewer problems (Olsen et al., 2014a). In our current study, all students solved the same number of problems (i.e. had the same amount of practice), but the students working in the collaborative condition spent less time on the tutor. This was surprising; we expected to find the opposite (Lou et al., 2001). Collaboration may increase the time spent on each problem if students are discussing the solution. This is time that would not be spent in the individual condition. Our findings that students collaborating spent less time on the tutor could be due to students making fewer errors when collaborating, so they spent less time fixing those errors. To investigate this question, future work would need to analyze the learning that happened within the tutor and how it may have changed over time. By analyzing the process data, we could better understand what actions the students were taking with the tutor and where the efficiency gains were made.

While the collaborating students learned as much as their classmates who worked individually with regard to domain knowledge, they may have had more of an opportunity to develop their math reasoning skills and social skills by working with a partner. In a collaborative setting, students need to be able to construct their arguments well enough for their partner to understand their reasoning and are given the opportunity to ask questions (Chi & Wylie, 2014). This provides them with the opportunity to develop their math reasoning and to critique the reasoning of others. A next step would be to analyze the process data from the collaborative conditions to assess what opportunities the students had to explain their mathematical reasoning and to understand what the collaboration processes looked like that led to learning. A limitation of this study is that we did not assess social skills or mathematical reasoning skills for the students, which is where we would expect students collaborating to benefit beyond those working individually, as Rummel and Spada (2005) found that students who had an opportunity to collaborate had better knowledge about collaboration skills.

In summary, our findings show that both collaborative and individual learning with an ITS can be beneficial to young students. However, the process that the students go through for the learning may be different when working collaboratively compared to individually as indicated by less time being spent working with the tutor when working collaboratively. Students may benefit from having the opportunity to work both individually and collaboratively in a domain. Future work is needed to investigate how to best combine individual and collaborative learning and where in the process each would be appropriate. Individual and collaborative learning may lead to different learning processes, which raises the intriguing possibility that a combination of these modes might support more robust learning.

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Acknowledgments

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