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RESEARCH

Scaffolding group explanation and feedback with handheld technology: impact on students' mathematics learning

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Abstract Based on strong research literatures, we conjectured that social processing of feedback by cooperating in a small group setting—with social incentives to ask questions, give explanations and discuss disagreements—would increase learning. We compared group and individual feedback, using two technologies: (1) Technology-mediated, Peer-Assisted Learning (TechPALS), which uses wireless handheld technology to structure feedback in small groups as they solve fractions problems and (2) a popular desktop product, which provides feedback to individual students as they solve fractions problems individually. Three elementary schools participated in a randomized controlled experiment conducted in the 2007–2008 school year. Students in the TechPALS condition learned more than did the control group students, with effect sizes ranging from $d = 0.14$ to $d = 0.44$. Analysis of observational data confirmed that students in the TechPALS condition participated socially in questioning, explaining, and discussing disagreements, whereas students in the individual condition did not. We conclude that an integration of technology, cooperative activity designs and broader educational practices can lead to impact on students' mathematics learning.

Keywords Handheld computers · Wireless networking · Mathematics · Fractions · Cooperative learning · Group feedback · Feedback

Introduction

Improving mathematics learning is an important challenge worldwide. A growing consensus of scholars finds that this requires engaging students in connecting procedural and conceptual aspects of mathematics learning (Kilpatrick et al. 2001; The National Mathematics Advisory Panel 2008b). Pedagogically, engaging students in explanation (and

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related activities such as forming conjectures, making arguments, providing justifications, etc.) is one of the major pathways to the development of conceptual understanding (Chi et al. 1994). Classroom discourse encourages students to explain (Good and Brophy 2007) and can be promoted by cooperative learning (Slavin 1996). In this paper, we consider whether group feedback in the context of a cooperative task can increase conceptual activities, such as asking questions, giving explanations, critiquing peers' work, and thereby increase student learning of difficult concepts.

Our focus on small group work arose from three perspectives. First, assigning students to work on mathematics problems individually or in groups is a typical classroom routine for most mathematics teachers (Hiebert et al. 2003). Most practice, however, focuses only on procedural skills (Stigler and Hiebert 1997). We sought to use the time already allocated to practice to engage students in mix of procedural and conceptual activities. Second, computer technology can perform some of the work required to effectively structure small groups so that students have an opportunity to learn (Kollar et al. 2006; Weinberger et al. 2005). As we will describe later in more detail, computer technology can structure tasks in accordance with proven principles of cooperative learning and can provide group feedback. In the context of tasks that require cooperation, feedback at the group level can encourage social processing, which can encourage students to question, explain and discuss disagreements. Third, American teachers tend to emphasize procedures in full-class lecture and discussion. While exemplary practices have been described and promoted (Hiebert and Grouws 2007; Stein 2008), most investigators find extensive professional development is required to change teaching practice (Wei et al. 2009). Relatively speaking, as we will describe later, we saw that technology can structure small-group-classroom-work to provide opportunities to learn a balance of concepts and procedures without extensive professional development.

For the purposes of exploring these ideas, we conducted classroom research on group feedback around the topic of fractions in fourth grade. Our research question was: Will group-level feedback increase student engagement in explaining fractions concepts and skills to each other and consequently increase student learning?

The problem context: student difficulties with learning fractions

Addressing student difficulties with learning fractions has become a national priority in the United States (The National Mathematics Advisory Panel 2008a, b). Research shows that fractions are a difficult topic, for a variety of reasons including the difficulties with the notation (Saxe et al. 2001), the conceptual differences between the fractions and counting numbers (Hiebert and Behr 1988), the use of multiple representations and models (Carpenter et al. 1993), and poor instruction (Hiebert et al. 2003). Difficulties with rational number appear in fourth grade and continue through eighth grade (National Center for Education Statistics 2001). Analyses of data from the National Assessment of Educational Progress (NAEP) suggest that students at the fourth-grade level have difficulty with such tasks as representing $1/d$ on a figure divided into d parts, placing a fraction on a number line, and identifying the fraction that represents part of a set (Wearne and Kouba 2000). Likewise, students in fourth grade have difficulty with equivalence and ordering of fractions. The National Mathematics Advisory Panel (2008a, b) concluded that there were few interventions to improve fractions learning that had rigorous evidence of impact.

Underlying student difficulties are a combination of new computational procedures (such as finding a common denominator in order to add or subtract fractions) and conceptual conflicts between whole number and fraction understanding. Researchers in fraction learning have identified several distinct meanings for common fractions (Confrey

2008; Kieren 1976). Each meaning suggests at least one model for understanding fractions, and these models have been used to help students justify procedures and provide ways to "check" the results of procedures (Smith 2002). Students have difficulty tracking the use of rational numbers across multiple representations, yet these representations are essential to effective problem solving and understanding (Cramer and Henry 2002). TechPALS sought to use technology to provide those opportunities.

The approach: scaffolding group feedback and explanation during practice time

Our approach to scaffolding group feedback and explanation was based upon Eduinnova® software that had been previously designed and tested by Nussbaum and colleagues at the Pontificia Universidad Católica de Chile (Zurita and Nussbaum 2004). This software presents tasks to groups of three students via wireless handheld devices. To complete a task, a group must work cooperatively: all group members must do part of the task on their own handheld device. Once all group members have done their parts, feedback is provided to the group. The feedback, however, only tells the group whether all parts are right or if something is wrong. The software does not identify which student of the threesome made a mistake or how many students made mistakes. Prior observations of the Eduinnova software suggested that group-level feedback often resulted in rich discussions among the small group of students, with positive social behaviors such as asking each other questions, providing explanations, discussing disagreements (Cortez et al. 2005; Zurita and Nussbaum 2004).

We conjectured that the Eduinnova software could be particularly powerful for learning difficult conceptual content such as fractions, because its design builds upon three powerful sets of principles for learning: repeated practice, feedback, and cooperative learning. Below, we provide the theoretical basis for our conjecture, with the following three-step logic:

1. Students need repeated practice in activities such as asking questions, giving explanations, and discussing disagreements in order to connect conceptual understanding and mathematical procedures.
2. Feedback is important to the effectiveness of such practice and teachers rarely provide students with the feedback they need in order to improve, especially with regard to conceptual understanding.
3. Cooperative learning provides a technique for structuring group feedback in a way that encourages students to improve their questions, explanations, and discussions of disagreements. Technology can facilitate this technique.

Repeated practice

Research on learning emphasizes the importance of practice with the target tasks and providing learners with representational tools that facilitate learners' making connections between two types of tasks, those that are more conceptual and those that are more procedural (Ainsworth 1999; Schnotz and Bannert 2003). Effective tools include providing learners with the abstract representations of events, tasks, and situations that are needed for expert problem solving (Gick and Holyoak 1983) and providing them with prompts to use knowledge and skill learned in one task in a new one (Bransford and Schwartz 1999).

Because these practice principles are well established, we chose practice as the classroom time for our intervention. We did not seek to test the effect of practice in our experiment, but rather made similar opportunities for repeated practice the basis for both the experimental and counterfactual condition.

Feedback to students and teachers

Cognitive research on learning indicates feedback is important because it helps learners benefit from practice (Bangert-Drowns et al. 1991; Butler and Winne 1995; Kluger and deNisi 1996). Thorndike's (1913) classic studies of feedback show that learners benefit more from engaging in practice with specific tasks when they receive and make use of feedback. To be effective in improving learning, feedback must provide cues to learners on what is needed to bridge the gap between what they know now and what they need to know (Hattie and Timperley 2007). Learners use the feedback to increase effort and correct their errors (Kluger and deNisi 1996) and requiring overt responses (e.g., inputting a correct answer) to multiple opportunities to respond to feedback has been shown to have strong effects (Clariana and Lee 2001). In addition, feedback that encourages the development of self-explanations can provide students with important resources for solving problems (Chi et al. 1989, 1994). Feedback that is task-focused rather than person-focused provides cues that promote mastery or learning goals (Butler 1987).

A number of studies have found positive effects for providing feedback on student performance. In a meta-analysis of 58 studies, Bangert-Drowns et al. (1991) found a modest overall positive effect (+0.26) for feedback on student achievement. Studies on multiple-try feedback have also shown it to be slightly more effective for higher-order outcomes compared to verbatim outcomes, reporting a mean effect size of 0.08 and median effect size of 0.10 (Clariana and Koul 2005). A meta-analysis by Kluger and deNisi (1996) found higher effects when students were given feedback on the correctness of their solution methods, on their improvement from earlier trials, and when they were using computers. Finally, other individual investigators have found that some of the most effective forms of feedback (a) guide improvement on a student product as it is being made or (b) guide teachers to adjust students' instruction (Butler and Winne 1995).

In practice, the feedback that teachers typically provide students is not consistent with the guidance suggested in research. When teachers provide qualitative feedback on papers, they find often focus on assigning grades to student work, even though research suggests that formative qualitative feedback is what will motivate learning more (Black and Harrison 2001). Teacher-made tests rarely call on students to construct elaborated explanations, thus diminishing students' opportunity to learn from assessment questions and teachers' ability to develop fine-grained understandings of what students know and can do (Haertel 1986). Teacher feedback from assignments is rarely task-focused; often the feedback provided includes more person-focused praise or criticism (Beason 1993). Although teacher feedback is often delayed for pragmatic reasons, technology can provide immediate feedback and immediate feedback is more effective (Dihoff et al. 2004; Epstein and Brosvic 2002). We chose to focus on the social processing of feedback in small groups to overcome these limitations, for reasons that are elaborated in the next section. Whereas the experimental condition uses technology to support social feedback among students, the counterfactual condition uses technology only for individual and teacher-level feedback.

Cooperative learning

We selected cooperative learning as a means to organize social processing of feedback, with an emphasis on encouraging behaviors that are positively associated with using feedback effectively. The peer tutoring literature, for example, shows that peer tutors' perceptions of their social role and their motivational beliefs and attitudes influence their tutoring actions (Foot et al. 1990). Effective tutoring involves a variety of tactics such as explaining, questioning, assessment, and feedback (Merrill et al. 1992). Math gains are significantly higher for tutors trained to give conceptual explanations than tutors only trained to give corrective feedback; explaining may help students to improve the organization and accessibility of their knowledge (Fuchs et al. 1997). While cooperative learning is not identical to peer tutoring, it can provide a social structure for tasks that encourages these same positive behaviors.

Cooperative learning has a long track record in educational research and has been most often employed in elementary (primary) school. Two well-known key principles for designing effective cooperative learning situations are as follows:

1. *Positive interdependence*: The task should be designed so that individual contributions are needed for group success; "students need to know that they sink or swim together" (Johnson, Johnson, and Holubec 1998).
2. *Individual accountability*: The task should be designed so that individuals have their own work to do and cannot expect to succeed by freeloading on the efforts of their partners.

Meta-analytic studies of cooperative learning have found a positive effect for cooperative learning interventions that incorporate these factors. In a review of 104 studies, Johnson and Johnson (Johnson and Johnson 1987) found an effect size of +0.78 favoring cooperative learning over individual learning. In a review of 52 studies, Slavin (1996) found a +0.32 effect size favoring reward structures in cooperative learning that include the features of positive interdependence and individual accountability. More specifically, we have identified several studies on cooperative learning in elementary school mathematics. Webb (1991) reviewed 17 studies linking peer interaction and achievement in elementary mathematics and found an average effect size of +0.53 for giving explanations and +0.45 for receiving explanations. More recently, the NMP conducted a meta-analysis of several cooperative learning strategies (Gersten et al. 2008), finding a significant pooled effect size of +0.38 for Team-Assisted Individualization and a significant pooled effect size of +0.43 for Peer-Assisted Learning Strategies. The NMP (2008b) also identified success factors in cooperative learning, including the following: formation of heterogeneous teams in which group members provide each other with feedback, teachers' ability to identify and target student deficiencies, a group reward structure that motivates students to help each other, and students' changing teams regularly so that they experience a variety of roles. Slavin (1996) discusses the mechanisms underlying cooperative learning. One key mechanism is *cognitive elaboration*. Cooperative tasks can create a need for cognitive elaboration because students need to explain the material to their peers. Webb (Webb 1991) in particular, links the gains in peer learning to behaviors of giving and receiving help; students should be trained or guided to engage in cognitive elaboration; otherwise they can default to simply giving the answer.

Despite the strong evidence in favor of cooperative learning, implementation problems can prevent replication at scale. In most studies, investigators have closely controlled the training of students in a specified cooperation regime and have closely monitored the classrooms to ensure implementation fidelity. The costs of scaling a program that relies on experts to train and monitor students are enormous. Hence, our approach sought to use technology, rather than extensive teacher training, to achieve the benefits of repeated practice of explanation in small groups, with group-level feedback, structured using principles of cooperative learning.

The TechPALS intervention

The TechPALS intervention comprised a database of content specific to fractions, Eduinnova software for handheld devices, and training modules on cooperative learning for both teachers and students.

Fractions content

We designed TechPALS as an intervention only for the portion of classroom time designated for student-centered practice and as a complement to the textbooks and instructional approaches teachers were already using. Students were expected to solve a series of fractions problems over the course of a single session encountering multiple representations of fractions. The different activity formats described below provided students with encounters with different meanings of fractions: students not only had to locate fractions on a number line (or compare locations of two numbers on the number line), they had to solve problems of the "*a*/*b* of" type, recognizing equivalence as an invariant relationship between two entities even as the specific quantities changed. As much as possible, we tried to ensure this content was consistent across the two conditions we tested.

Eduinnova software

We built specifically on work conducted by Zurita and Nussbaum (2004), to develop a platform of software activities for wireless, handheld devices, which they termed Eduinnova. These activities were not specifically mathematical, but could be adapted to mathematics tasks.

Three activities drew our attention as fitting our target domain of fourth-grade fractions: *Consensus*, *Exchange* and *Aiming Between*. We describe each briefly below, with specific attention to how they provide group feedback and create a need for social processing among students as part of practice. Because technology can provide instant feedback as a group engages in a mathematics task, we were able to more closely link the motivational and cognitive aspects in time and in the task structure. Further, more rapid, iterative cycles of group performance and group reward should help students improve more quickly. Indeed, Fantuzzo et al. (1992) showed the benefits of integrating the task and reward components.

We also used the handheld technology to overcome challenges often associated with cooperative learning activities. In particular, we used technology to support high-quality implementations by automatically assigning specialized mathematical tasks to students, requiring every student to perform work for which they are individually accountable, and automatically aggregating feedback at the group level for both students and teachers.

Consensus

In the *Consensus* activity (Cortez et al. 2005), each student in the group of three receives the same multiple-choice question at the same time (Fig. 1). Each student enters an answer independently (individual accountability); however, the system requires that students agree on an answer (positive interdependence) and provides feedback only at the group level. If students do not choose the same answer, the software tells them they must agree, which generates much discussion. Once students agree, the software tells them whether they were all right or all wrong (formative assessment). If wrong, they must try again, while the software makes the previously incorrect choice unavailable so that students individually select a different answer until they select the correct one.

Exchange

In the *Exchange* activity (Zurita and Nussbaum 2007), each student receives two representations of a fraction, such as a numeral representation and a pie representation (Fig. 2). Each student's goal is to match the representations on his or her screen. A match is achieved if the representations depict equivalent fractions. To achieve a match, students exchange representations within their group (positive interdependence). When all three students think they have a match, they check their answer. Similar to *Consensus*, the software tells the students only that all the matches in the group are correct or that at least one student does not have a match (formative assessment). The students determine who has the mismatched representations. Because of the need to both exchange representations and find mismatches, students have to engage in cooperative negotiations. Further, because one student may have the numeral 5/6 and another student a pie showing 10 of 12 shaded sections, the students are encouraged to explain to each other why particular representations are or are not equivalent.

Aiming Between

The *Aiming Between* activity consists of two parts: generating a unique fraction and evaluating fractions on a number line. Each student in the group of three receives the same

Fig. 1 Consensus activity with group-level feedback on answer agreement

Fig. 2 Exchange activity

representation of a number line with a target interval highlighted (Fig. 3). The number line always starts at 0 and ends at 1; however, it varies in terms of target interval length and location as well as the number of tick marks, which are always in equal intervals. Each student constructs a fraction that would fall within the highlighted target interval. For example, if the target extended from 24/100 to 51/100, a correct response would be any fraction greater than or equal to 24/100 and less than or equal to 51/100. After each group member enters an answer independently (individual accountability), the system verifies that each student has submitted a unique fraction (equivalent fractions are accepted). If a group member enters an answer that was already given, the system instructs the member to submit a unique answer. Once each member submits a unique answer, the system allows the group to proceed to an evaluation screen. Each group member evaluates whether each of the three answers fall within or outside the target interval. The system instructs the group to come to a consensus whenever there is disagreement in the evaluation, and the activity proceeds much in the style of Consensus. Again, feedback occurs only at the group level; students must agree (positive interdependence); and the software indicates correctness while also providing the opportunity to revise incorrect responses (formative assessment).

Feedback to the teacher

Across all activities, the teacher receives real-time feedback on how the groups performed on each question. Feedback is displayed as a simple grid of groups (rows) by problems (columns) as displayed in Fig. 4. A cell in the grid is colored green if the group gets that problem right on the first attempt, yellow if the group gets the problem right on a later attempt, and red if the group exceeds the number of allowed attempts. By scanning the grid, a teacher can identify groups that are having trouble (many red cells in the row) and provide assistance. Alternatively, the teacher can focus on a particular problem (many red cells in a column) that requires additional explicit teaching. Thus, the teacher can use formative feedback to adapt the instruction to fit emerging student needs.

Assignment of students to groups

As will be discussed later, we randomly assigned students to either a TechPALS or a control condition, and students stayed in the assigned condition for the duration of the study. In addition, students in the TechPALS condition worked each day in a different group of three

Fig. 3 Aiming Between activity

Fig. 4 Teacher feedback display

students. The software randomly assigned these small working groups each day. Although there has been some debate about the ideal composition of groups for learning (Johnson and Johnson 1987), in practice it is very difficult to implement grouping strategies. Daily random assignment gives students the benefit of working with different partners; it "spreads the wealth" of good cooperative partners and minimizes the inequity of any one student having to cope with a particularly undesirable combination of partners for too long.

Training on cooperative learning

To encourage TechPALS students to engage in explanation and other appropriate collaborative behaviors, we developed *The Cooperagent,* a short multimedia presentation and storybook about an agent who learns cooperative learning behaviors. *The Cooperagent* presents two scenarios showing Cooperagents, characters who are about 12 years old, in groups of three using key cooperative learning behaviors of asking and answering how and why questions while trying to solve math problems. The story's characters modeled and emphasized the importance of eliciting and providing explanations ("ask and answer how and why") rather than merely asking for and giving the answers. We introduced *The Cooperagent* in the beginning of the intervention and relied on teachers to reinforce the behaviors throughout the intervention. Students also received print collateral to which they could refer back.

Experimental design

After conducting a pilot study in the prior school year (Roschelle et al. 2009), we designed a randomized experiment to address the following research question:

> Will group-level feedback (as scaffolded by TechPALS' package of handheld software and Cooperagents training) increase student engagement in explaining mathematics to each other (and related positive social learning behaviors) and consequently increase student learning?

The study team randomly assigned students to solve fractions problems using either TechPALS or a commercial software application that provided students with solo practice opportunities with individual feedback. We compared TechPALS to alternative software so as to rule out the possibility that any differences in learning were caused by students' excitement about technology (a potential Hawthorne effect) and to make sure both conditions received feedback. For our control intervention, we selected iSucceed Math (formerly Larson Intermediate Math), a widely used commercial-grade software.

iSucceed Math organizes practice sessions into three sections: presentation of a lesson such as area model of fractions with audio–visual demonstrations, an assisted practice section with problems on the lesson's topic, and then a challenge section with a battery of math problems on the lesson topic that students must pass with a score of 80% or better (this criterion was recommended by the vendor and agreed to by the teachers in the study). Individual feedback is a defining element of the assisted practice sections with the system providing feedback to the student on each answer. To complete an assisted practice section, a student must correctly answer four questions. A student is presented a question, usually a constructed response. After the student submits a response, the system evaluates whether the response is correct or incorrect and provides non-elaborated feedback. If the student has answered correctly, she progresses to the next question. If she has answered incorrectly, the software prompts her with "Check your work" and offers her the opportunity to try again or to see the answer. After three incorrect attempts at the same problem, the system gives the student the choice of reviewing the presentation section or seeing the answer. Students in this condition used desktop or laptop computers individually. The mathematical topics of the practice sessions were aligned with the content being offered in the treatment condition. While students worked at their own pace, the classroom teacher would typically circulate through the room and help students individually, usually in response to a student asking for help.

Participants

We recruited two classrooms of fourth-grade students from each of three elementary schools in the San Francisco Bay Area. All three schools were selected because they were in the middle of the distribution of schools on California's Academic Performance Index (API). On this basis of the API, schools are ranked from 1 to 10 (from low to high); we selected schools with APIs of 4 or 5 (see Table 1). We selected average-performing

Table 1 Demographics of participating schools

School	Grades	School size (number of students)	2005-06 State rank (API)	Students on free/reduced-price lunch (%)	English language learners (%)	Title I
1	K-6	516	5 (750)	46.1	42.6	Yes
2	K-5	462	5 (746)	62.3	52.2	Yes
3	K-5	412	4 (732)	67.7	39.3	Yes

schools, so that in this early stage of intervention development, we could observe the potential impacts of TechPALS under conditions where basic technology infrastructure to support implementation existed in the schools. All three schools participated in Title I and had from 42 to 67% of their student population in the free or reduced-price lunch program, suggesting moderate poverty. The distribution of students across ethnicity groups within the participating schools was predominantly Hispanic (51%), Asian (21%) and White (18%), with minor representation of African American (6%) and others (4%). Data were gathered from 173 students across the three schools ($n = 57$ at School 1; $n = 60$ at School 2; $n = 56$ at School 3). Achievement data were missing for 12 students across the three schools due to students being absent on the days achievement data were collected.

Procedure

During the first half of each mathematics period, classroom teachers provided their normal classroom instruction to their students. Then, for the portion of the class period devoted to student-centered practice, we randomly assigned half the students from one teacher to exchange classrooms with half the students from the second participating class (see Fig. 5). In one of the two randomly assigned and newly mixed classrooms, students used TechPALS for practice whereas the other classroom used iSucceed Math. In School 1, 28 students were assigned to the treatment condition and 29 to the control condition. In School 2, 30 students were assigned to the treatment condition and 30 to the control condition. In School 3, 28 students were assigned to the treatment condition and 28 to the control condition. Teachers were also randomly assigned condition and swapped assignments during the second half of the trial (students remained in the same condition throughout). After the practice portion, students and teachers returned to their original arrangements. This design counterbalanced the teacher effects across the two conditions, particularly the effects of instruction provided by different teachers. Further, the design ensured that students in both conditions spent the same amount of time practicing fractions with technology. Because we used random assignment to form the mixed classrooms, we have no reason to suspect any systematic bias due to the classroom of origin. Students were given a pretest on the first day of the experiment and an identical posttest on the last day of the experiment, with approximately 12 days of instruction and practice in between.

Instruments

Observation protocol for measuring implementation fidelity

To capture implementation fidelity and describe differences in the two classroom conditions, we created an observation protocol that focused on what students were saying and

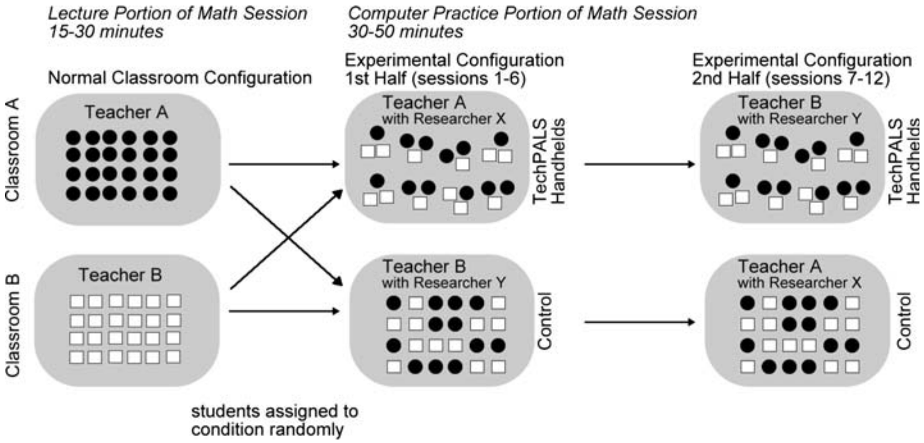

Fig. 5 Random assignment and procedure

doing. We began with a review of literature and existing observation protocols (Dynarski et al. 2007; Good and Brophy 2007; SRI International 2004; Webb 1991). Multiple design iterations resulted in a protocol that captured the following elements in each 10-min observation window:

1. *Classroom activity overview* (first minute). How many instructional activities were occurring at a given point, what the teacher's role was, what percentage of students were off-task, and how many students were using the target application.
2. *Student behaviors* (second through seventh minutes). How many math questions a student asked of other students, how many times a student provided an answer to another student, how many times a student gave a mathematical explanation to another student, manipulating one's own handheld computer, manipulating a partner's computer, performing calculations on paper.
3. *Teacher activity* (eighth through tenth minutes). Explaining a math concept to the whole class, giving directions, etc.

Time sampling was used to meet two of our primary measurement goals, systematic capture of key implementation variables over the class period and observation of every student in the experiments. A team of six trained researchers conducted the observations, which occurred in back-to-back 10-min blocks as the students used the software. Observers were randomly assigned to the condition on each observation day. During the student behavior-focused period of an observation, observers maintained focus on an individual student's behaviors. The team of observers was not blind to the experimental condition due to the technology intervention being used in the two conditions, thus introducing some potential for observer bias. Potential observer bias was minimized by anchoring observation elements to particular behaviors (e.g., observations of students' raising hands, asking questions, making collaborative move), thus requiring relatively low inference. The team of observers received extensive training using the protocol on video samples of students from our pilot studies.

Our inter-rater reliability checks examined observers' agreement of a behavior occurring in both conditions. In order to determine reliability, pairs of observers simultaneously coded a subset of classroom periods. We found that observers attained 90% reliability on their counts of specific behaviors, with an allowed error of ±1 count per 6-min time period. The development of this measure and results from the pilot test of the observation protocol are reported by Rafanan et al. (2008).

Student fractions knowledge test

To measure outcomes, we used a 29 item assessment that included 20 items from a published test of fractions concepts and procedures, developed by Saxe et al. (2001). We did not use the complete Saxe assessment, because it included items that aimed at fifth-grade skills and concepts. We excluded those items that assessed skills or understanding of concepts that were beyond the scope of the fourth-grade content that our treatment and control interventions presented (e.g., items requiring adding and subtracting fractions with unlike denominators were dropped). To broaden coverage of fourth-grade concepts and procedures and to increase the assessment's reliability, we added nine items from our pilot test work based on released items from various state standardized fourth-grade mathematics tests. The content in the TechPALS intervention as well as in the control condition was aligned to the assessment, and the assessment items chosen were aligned to the conditions' content in order to assess students' abilities on concepts and procedures that the students had opportunity to practice during the experiment. The overall test included items requiring students to identify multiple representations of fractions (9 items), identify fractions on a number line (2 items), construct or identify equivalent fractions (9 items), create equal partitions (3 items), add and subtract fractions (2 items), convert mixed numbers (2 items), and solve word problems with fractions (2 items). The resulting test had 29 items, which was the maximum score students could obtain on the pre- and post-test, and the test indicated good overall reliability ($\alpha = 0.83$).

Results

The independent variable in this study was condition (TechPALS or control); the dependent variables were observed frequencies of behaviors and pre-post gain scores on the student fractions knowledge test. After discussing the equivalence of groups on the fractions test at pretest, we discuss the observed differences in student behaviors and learning.

Baseline differences between treatment and control classrooms

Means for the pretest were not different between the two experimental conditions ($t(159) = -0.19$, n.s.). Means for the pretest were significantly different among the three schools ($F(2, 158) = 12.89$, $p < 0.001$), with School 2 reporting higher pretest means ($M = 12.84$, SD = 6.28) than School 1 ($M = 7.77$, SD = 3.73) and School 3 ($M = 10.11$, SD = 5.16). We note that School 2 started teaching fractions before the pretest, which could account for that school's higher mean pretest score.

Impacts on practice

Observational data support the idea that the group feedback provided by TechPALS increased social processing of feedback. We tallied the observations of each behavior per 6-min observation window in both TechPALS and control conditions. We used the Mann–

Whitney test because the resulting data were not normally distributed. Both groups were observed to spend substantial time practicing with fractions by performing calculations; however, we found that behaviors compatible with social processing of feedback occurred significantly more frequently in the TechPALS condition (see Fig. 6 and Table 2). These include reading a problem aloud, asking a mathematical question, giving an explanation, making a collaborative move, directing a peer, and disagreeing with another student. The only behavior that occurred significantly more often in the control condition was raising a hand (to call the teacher). Consequently, it seems plausible that any observed gains in the treatment group could be produced by an increase in social processing of group feedback, including such behaviors as asking a math question, giving and explanation, and discussing a disagreement.

Analysis of the impact of TechPALS on students' fractions knowledge

To examine group differences, we used a 2 (experimental condition) × 3 (school) ANOVA with students' gain score on the assessment as the outcome variable (Table 3). We did not model the effects of clustering TechPALS students in triads because the TechPALS software randomly assigned students to a different triad in each practice session. Overall, students learned from pre- to post-test in both conditions. We found a significant main effect of experimental condition ($F(1, 155) = 4.08$, $p < 0.05$, Cohen's $d = 0.22$), with TechPALS students learning more ($M = 6.38$, $SD = 4.17$) than those in the control condition ($M = 5.24$, $SD = 3.92$). In addition, we found a main effect of school ($F(2, 155) = 24.03$, $p < 0.001$), with post hoc tests indicating School 2 had a significantly lower gain than School 1 and 3 (Tukey's HSD, $p < 0.05$). This could be explained by an additional observation. Only School 2 offered instruction in fractions *before the pretest*. It could be that if we had measured School 2 at three points in time (adding an earlier pretest before any fractions instruction was given), we would see more commensurate gains overall and that a portion of the overall gain was due to prior ordinary instruction. In each school, the effect favored the TechPALS condition, even though the effect sizes varied across the three schools (Cohen's $d = 0.44$ in School 1; Cohen's

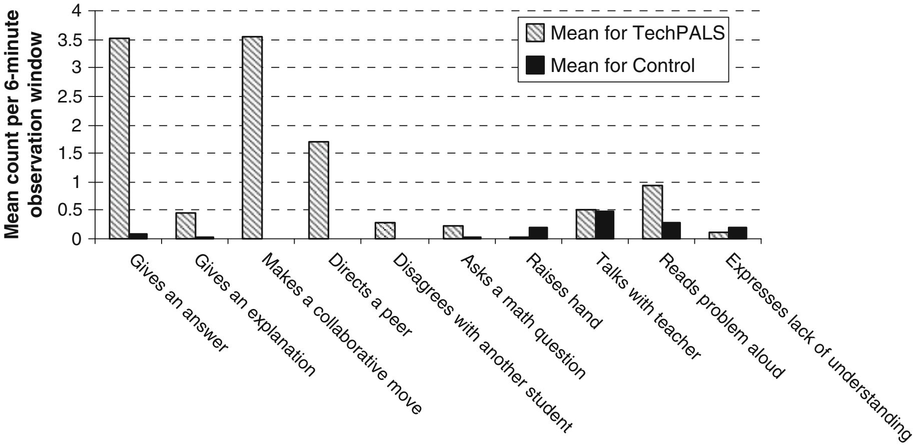

Fig. 6 Observed cooperative learning behaviors

Table 2 Results from Mann–Whitney *U*-test comparing observed behaviors per 6-min observation window

Behaviors	Mean for TechPALS condition	Mean for control condition	Mann–Whitney *U*-test	*p* value
Gives an answer	3.52	0.08	795	0.000
Gives an explanation	0.45	0.03	2875	0.000
Makes a collaborative move	3.56	0.00	1247	0.000
Directs a peer	1.71	0.00	1806	0.000
Disagrees with another student	0.28	0.01	3136	0.001
Asks a math question	0.24	0.02	3348	0.026
Raises hand	0.04	0.19	3186	0.005
Talks with teacher	0.52	0.47	3596	0.791
Reads problem aloud	0.93	0.28	2811	0.001
Expresses lack of understanding	0.12	0.20	3561	0.602
n	85	86		

$d = 0.14$ in School 2, and Cohen's $d = 0.17$ in School 3) (see Fig. 7). There was no significant interaction effect of the condition and school factors ($F(2, 155) = 0.20$, n.s.).

We also analyzed the data by gender and found no significant difference on gain scores between boys and girls across the sample, ($t(159) = 1.417$, n.s.) with girls ($M = 6.28$, $\mathrm{SD} = 3.61$) obtaining similar gain scores as boys ($M = 5.37$, $\mathrm{SD} = 4.41$). Additionally, a median split on pretest scores of students within the TechPALS condition revealed a significant difference in the gain scores reported by students in the two pretest achievement groups ($t(159) = 5.554$, $p < 0.001$). Students scoring low on the pretest assessment reported higher gains on the posttest assessment ($M = 7.42$, $\mathrm{SD} = 3.86$) than students who scored high on the pretest ($M = 4.15$, $\mathrm{SD} = 3.61$). As this could represent regression to the mean, it is difficult to interpret. It is worth noting that the TechPALS condition supported learning for students with either low or high pretest scores. Students do not need high incoming content knowledge to benefit from small group work.

Discussion

We found that students in all three schools learned more with the TechPALS intervention than in the control condition. The control provided a strong counterfactual because it provided feedback to individuals and it allowed us to control for the possibility that student learning might merely be related to the excitement of using technology. Further, the content in TechPALS was comparable to the mathematical content in the control's software. In addition, because we counterbalanced teachers, we have confidence that observed differences are not due to differences in how teachers taught their classrooms outside of the practice sessions. The use of random assignment also reduces threats to internal validity due to selection of students into the treatment based on particular characteristics.

Based upon prior uses of technology to structure group work (Kollar et al. 2006; Weinberger et al. 2005) and the importance of the social activities for cooperative learning (Good and Brophy 2007), we theorized that TechPALS could benefit students because of its support for group feedback and social processing. Our observational measures support the interpretation that group feedback and social processing was a significant component of the

Table 3 Descriptive statistics for student learning scores in the TechPALS and control groups, across the three schools

	TechPALS group			Control group		
	Gain score	Pretest	Posttest	Gain score	Pretest	Posttest
School 1						
M	8.16	7.64	15.80	6.52	7.89	14.41
SD	3.90	3.13	3.57	3.06	4.26	4.57
N	25	25	25	27	27	27
School 2						
M	3.59	13.00	16.59	2.69	12.69	15.38
SD	3.05	6.11	5.35	3.90	6.55	5.72
n	27	27	27	29	29	29
School 3						
M	7.58	9.81	17.38	6.70	10.41	17.11
SD	4.02	5.15	5.61	3.38	5.26	4.13
N	26	26	26	27	27	27
Overall						
M	6.38	10.22	16.60	5.24	10.39	15.63
SD	4.17	5.40	4.93	3.92	5.75	4.94
N	78	78	78	83	83	83

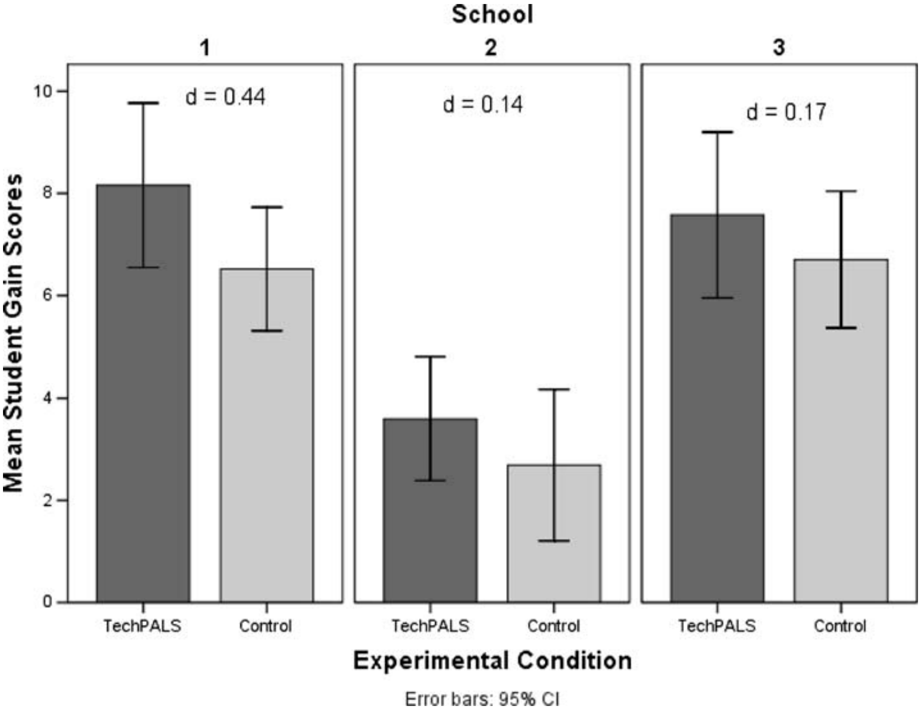

Fig. 7 Mean student-learning gains across three schools

intervention; feedback and social processing behaviors occurred far more frequently in the TechPALS condition than the control condition. In addition, the literature review argued that engaging in explanations is one of the major pathways to conceptual understanding (Chi et al. 1994). Observations show that in the TechPALS condition, each student produced about 3 explanations (on average) per each practice session. Reading a problem aloud, asking a mathematical question and disagreeing with a peer were all higher in the TechPALS condition as well, behaviors common in successful implementations of cooperative learning (Webb 1991). While these implementation measures are consistent with and support TechPALS program theory, further experimentation would be necessary to more rigorously isolate each potential factor within TechPALS and determine which are necessary and sufficient.

Our study findings may not generalize to schools with more limited technological infrastructure or to schools where behavior management problems are more severe than they were in our schools. At the same time, we obtained our results in schools that had large Hispanic populations and moderate levels of poverty and we see no particular reason why TechPALS would not work in schools with student populations with different cultural and ethnic backgrounds or with less poverty. Given the small number of schools we worked in, however, more evaluation research is needed to support the claim that TechPALS can work in a wide variety of school settings.

The TechPALS intervention occurred concurrently with ordinary instruction in fractions; the overall gains from pretest to posttest reflect not only the intervention but also the normal instruction teachers' provided. We saw several ways in which both this instruction and its relationship to TechPALS could be improved. First, we noted that the textbooks were confusing and fast-paced. Better curricular materials could produce stronger learning gains, and this effect could be compounded with the TechPALS software. Following our review of cooperative learning principles, we were concerned that textbooks did not provide sufficient base knowledge to support student explanation. If textbook provided better explanations, then the students might provide better explanations to each other in cooperative learning when using TechPALS. Consistent with the findings from the TIMSS international comparison (Stigler et al. 1999), we noted that the teachers tended to emphasize procedures without concepts. If the teachers presented a more balanced approach, it would likely prepare students to learn more during TechPALS practice.

In future work, we hope to take a more comprehensive approach and develop a curricular activity system that carefully integrates (1) the technology for structuring small group practice with (2) curricular materials that are coherent and focus on conceptual understanding, and (3) teacher professional development to support teachers' needs for mathematical content knowledge as well as new routines for cooperative learning and formative assessment. We anticipate that a productive learning environment will result from the development of materials that integrate procedural fluency and conceptual understanding and the creation of structured opportunities to support the practice of these difficult aspects of fractions.

Finally, we discovered the limits of the current generation of TechPALS technology, which ran counter to our initial conjecture of its potential to reduce the barriers to implementing feedback well (e.g. Black and Harrison 2001; Haertel 1986; Beason 1993). We conjectured that technology would be much better able to coordinate the rapid assignment of cooperative learning tasks to students and could provide immediate, response-specific feedback (Dihoff et al. 2004; Epstein and Brosvic 2002). Nevertheless, we observed technology delays and failures in the TechPALS condition leading to a reduction of time on task. The handhelds were prone to break (around 20% of the handhelds broke over a three-week interval), and the wireless network was prone to go down, requiring fairly complicated procedures to get it working again. As much as 7 min of classroom time was wasted each day on technology set up. The technology needs to be more reliable before one could reasonably claim it makes it easier to implement cooperative learning well.

Conclusion

We see small group practice of tasks that link conceptual understanding and mathematical procedures as a genre of activity that can be further supported using technology. Although a great deal of work is taking place using technology for individual feedback, the opportunities to structure and provide feedback in small group settings is under-explored. The TechPALS intervention demonstrates a fertile activity framework for organizing students' work in small groups and suggests the possibility for extensions to other math topics and subject areas. In fact, research groups in Chile, other Latin American countries, and the UK are conducting additional research with Eduinnova software at a variety of age levels and school topics (Bustos and Nussbaum 2009; Galloway 2007; Nussbaum et al. 2009). Further experimental research could also seek to pinpoint the causal contribution of each of the factors in the integrated TechPALS intervention (e.g. the contribution of specific activities, the contribution of specific social behaviors, the contribution of specific types of feedback), which were too fine-grained to pinpoint in one modest-sized study.

We also note the opportunity to reuse principles of cooperative learning (e.g. Johnson et al. 1998) to structure tasks delivered by technology. By using technology to organize cooperative learning. Traditional cooperative learning approaches require extensive teacher professional development and monitoring of implementation fidelity. Technology may enable innovators to harness the benefits of the cooperative learning activity structures in more easily implemented formats and may allow more focused professional development.

Finally, we observe that networked handheld devices and cell phones are growing in availability and capability, but insufficient experimental evidence of enhanced mathematics learning is available to support policy decision-making (The National Mathematics Advisory Panel 2008b). Promoters of laptop computers have advanced the notion that handheld device personalize learning, although strong evidence of the benefits of personalization has been hard to find. Our research with TechPALS suggests that using handhelds to scaffold small group learning may be an important approach to explore further, because technology can socialize learning, encouraging positive behaviors such as asking questions, giving explanations, and discussing disagreements. These social behaviors, in turn, may engage students in connecting conceptual and procedural aspects of mathematics content.

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