Is self-explanation worth the time? A comparison to additional practice

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Structured Abstract

Background: Self-explanation, or generating explanations to oneself in an attempt to make sense of new information, can promote learning. However, self-explaining takes time, and the learning benefits of this activity need to be rigorously evaluated against alternate uses of this time.

Aims: In the current study, we compared the effectiveness of self-explanation prompts to the effectiveness of solving additional practice problems (to equate for time on task) and to solving the same number of problems (to equate for problem-solving experience).

Sample: Participants were sixty-nine children in grades 2 through 4.

Methods: Students completed a pretest, brief intervention session, and a post and retention test. The intervention focused on solving mathematical equivalence problems such as $3+4+8=\_\_+8$. Students were randomly assigned to one of three intervention conditions: self-explain, additional-practice or control.

Results: Compared to the control condition, self-explanation prompts promoted conceptual and procedural knowledge. Compared to the additional-practice condition, the benefits of self-explanation were more modest and only apparent on some subscales.

Conclusions: The findings suggest that self-explanation prompts have some small unique learning benefits, but that greater attention needs to be paid to how much self-explanation offers advantages over alternative uses of time.

Self-explanation is a conceptually-oriented learning activity that has intuitive appeal and empirical backing. It is defined as generating explanations to oneself in an attempt to make sense of new and known to be correct information (Chi, 2000). Prompting for self-explanation benefits learning in many domains, such as mathematics, reading, electrical engineering, and biology, and in wide-ranging age groups, from 4-year-olds to adults (e.g., Ainsworth & Loizou, 2003; Calin-Jageman & Ratner, 2005; Graesser & McNamara, 2010; Mayer & Johnson, 2010; Rittle-Johnson, Saylor, & Swygert, 2008). However, prompting to self-explain increases study time, and few studies have evaluated whether it is worth this increase, relative to alternative uses of time. In the current study, we compared the benefits of prompts to self-explain to additional practice and a control condition for children learning a key mathematics topic. Our goal was to elucidate the roles of self-explanation, amount of practice and study time.

Benefits of Self-Explanation

Explaining while making sense of new correct information is a constructive learning activity that increases knowledge through a variety of routes (Chi, 2009; Fonseca & Chi, 2010). In particular, self-explanation can support both conceptual and procedural knowledge.

Conceptual knowledge entails an understanding of principles governing a domain and the interrelations between units of knowledge (Bisanz & LeFevre, 1992; Greeno, Riley, & Gelman, 1984; Rittle-Johnson, Siegler, & Alibali, 2001) Self-explanation can benefit conceptual knowledge by focusing attention on relevant, underlying principles. Specifically, self-explanation can repair and enrich existing knowledge to make it more accurate or better structured, and facilitates the construction of inference rules used to form general principles (Chi, 2009; Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Fonseca & Chi, 2010).

Self-explanation can also improve procedural knowledge, or the successful execution of action sequences for problem solving (Anderson, 1993; Rittle-Johnson & Alibali, 1999). The act of self-explaining can broaden the range of problems children apply correct procedures to (i.e., promote procedural transfer), and promote invention of new procedures (Lombrozo, 2006; Rittle-Johnson, 2006; Siegler, 2002). Students may gain insight about the rationale of a procedure through self-explanation, and this may lead to improved transfer (Rittle-Johnson, 2006).

Past Research on Self-Explanation in Problem-Solving Domains

Given our interest in conceptual and procedural knowledge, we briefly review past research on prompting for self-explanation in problem-solving domains, where both types of knowledge are important. Indeed, prompting for self-explanation benefits procedural (e.g. Atkinson, Renkl, & Merrill, 2003; Curry, 2004; Pine & Messer, 2000; Rittle-Johnson, 2006), and conceptual knowledge (e.g. Aleven & Koedinger, 2002; Berthold & Renkl, 2009). Across these studies, learners in the self-explanation condition responded to prompts that encouraged them to make inferences from material known to be correct (or incorrect), whereas the control condition did not. For example, in a study on addition learning, kindergarteners observed an expert solving a problem and those in the self-explanation condition were prompted to explain how the expert knew the answer (Calin-Jageman & Ratner, 2005). What matters is that learners attempt to revise their understanding and make sense of the material, even if they are unsuccessful in articulating a correct explanation (e.g. Atkinson et al., 2003; de Bruin et al., 2007). Indeed, responses are often not complete or coherent, and can be partial or incorrect (Chi, 2000; Renkl, 2002; Roy & Chi, 2005).

The effect of prompting for self-explanations must be compared to a control group that was not prompted to explain. In most studies, the two conditions worked through the same number of problems, and the self-explanation condition spent additional time providing explanations. Thus, the self-explain condition had the double benefit of more time thinking about the material *and* explaining.

Self-explanation requires a significant amount of time compared to working through practice problems alone; often about twice as much time (Chi, Leeuw, Chiu, & Lavancher, 1994; Matthews & Rittle-Johnson, 2009). The contribution of additional time on learning outcomes is not trivial. In fact, time spent on learning is strongly related to quality of learning (Bloom, 1968, 1974; Ericsson, Krampe, & Tesch-Romer, 1993; Logan, 1990; Stallings, 1980). Self-explanation cannot be cited as the sole cause of learning unless time on task is comparable across conditions.

In real-world learning environments, if study time were not devoted to self-explaining, students would likely complete more problems. Having students spend additional time solving problems could increase procedural and conceptual knowledge, particularly when the problems are unfamiliar. Problem-solving practice strengthens correct procedures and can support the acquisition of more efficient or generalizable procedures (e.g., Imbo & Vandierendonck, 2008; Jonides, 2004). It may also weaken incorrect procedures (Siegler, 2002). When students are solving unfamiliar problems, problem-solving practice may also improve conceptual knowledge because the student must construct their own procedures, which may activate and strengthen relevant concepts (Chi, 2009).

Surprisingly, only two published studies compared the effectiveness of self-explanation prompts and additional practice to make time on task comparable, and the results are mixed. There was no benefit of self-explanation prompts for elementary students learning about

mathematical equivalence compared to students who practiced twice as many problems (Matthews & Rittle-Johnson, 2009). However, this study provided conceptual instruction, which may have lessened the need for explanation prompts. The other study did find a benefit of self-explanation for conceptual knowledge and procedural transfer in high-school students learning geometry (Aleven & Koedinger, 2002). Notably, students who self-explained referenced a glossary containing conceptual information and received feedback on their explanations, which is very different from other studies where explanations were generated without help or feedback. Overall, the relative merits of practice versus prompting for self-explanation are largely unknown.

Current Study

The current study compared the benefits of self-explanation prompts to two alternatives: solving the same number of problems to make amount of practice experience comparable, and solving additional practice problems to make time on task comparable. As in most self-explanation studies, we did not provide instruction on domain concepts or feedback on self-explanation quality.

We examined the benefits of self-explanation with students learning to solve unfamiliar problems involving operations on both sides of the equal sign (e.g., $3+5+6 = \_+6$, a mathematical equivalence problem). These problems tap the idea that the amounts on both sides of an equation are the same, which is a foundational concept that links arithmetic to algebra (Kieran, 1981; MacGregor & Stacey, 1997; Matthews, Rittle-Johnson, McEldoon, & Taylor, 2012). Unfortunately, elementary children often interpret the equals sign as an operator that means "adds up to" or "get the answer," and reject equations written in non-standard formats (e.g., "3+4=4+3" or "5=5") (Baroody & Ginsburg, 1983; McNeil & Alibali, 2005; Rittle-Johnson &

Alibali, 1999). They generally have little prior experience solving mathematical equivalence problems and tend to solve such problems incorrectly (Alibali, 1999; Perry, Church, & Goldin-Meadow, 1988).

In the current study, the *self-explain* condition solved six problems and was prompted to self-explain after each. The *control* condition also solved six problems but was not prompted to self-explain. The *additional-practice* condition solved twelve problems and was not prompted to self-explain. A prior study indicated that doubling the number of problems made intervention time comparable in this domain (Matthews & Rittle-Johnson, 2009). We assessed conceptual and procedural knowledge on a pretest, immediate posttest, and two-week retention test.

We hypothesized that: (1) the self-explain condition would have greater conceptual and procedural knowledge than the control condition. Past research has found that self-explanation improves procedural transfer on this task (Rittle-Johnson, 2006; Siegler, 2002), and we predicted improved conceptual knowledge as well based on research on other tasks (e.g., Berthold, Eysink, & Renkl, 2009; Hilbert et al., 2008). (2) The self-explain condition would have greater conceptual knowledge and procedural transfer than the additional-practice condition, based on the hypothesized benefits of self-explanation. (3) The additional-practice condition would have greater procedural knowledge than the control condition, based on the benefits of practice (Anderson, 1982; Imbo & Vandierendonck, 2008).

<div align="center">Methods</div>

Participants

The current study was conducted with students in Grades 2-4 from two urban parochial schools in the Southeastern United States serving middle-class, predominantly Caucasian populations. Consent to participate was obtained from 167 students and their parents. Our target

sample were students who struggled to understand mathematical equivalence. To identify

students who did not already have sufficient knowledge, and thus had room to improve, an initial

pretest score of less than 85% correct identified 108 children who were randomly assigned to an

intervention condition. However, our initial selection criterion was too generous, as some

students were near ceiling on the procedural knowledge measure, solved almost all the

intervention problems correctly, and approached ceiling on outcome measures regardless of

condition. We decided to adopt a stricter inclusion criterion by only including students who

scored at or below 75% correct on the procedural knowledge items, which is more in line with

past problem-solving studies that only used procedural knowledge scores to determine inclusion

(Calin-Jageman & Ratner, 2005; Matthews & Rittle-Johnson, 2009; McNeil & Alibali, 2000;

Rittle-Johnson, 2006). Of these 80 students, 11 students were dropped; three students'

intervention sessions were interrupted by unexpected school activities, one student received extra

math tutoring and the school asked us to exclude that student, one student accidentally received

tutoring twice, and 6 students were absent for the retention test. Of the 69 students included in

the final sample, 34 were in Grade 2 (16 girls), 23 were in Grade 3 (16 girls), and 12 were in

Grade 4 (5 girls). The average age was 8.8 years (range 7.4–10.7). Teachers reported discussing

the meaning of the equals sign and had presented mathematical equivalence problems before,

although infrequently. Children are not typically exposed to mathematical equivalence problems

(e.g. Falkner, Levi, & Carpenter, 1999), and the low-levels of exposure in this sample may

explain why a larger than usual number of students pretested out of the study.

Design

Participating students completed a pretest, intervention, immediate posttest, and a two-

week retention test. Students were randomly assigned to one of three conditions: control (*n=*17;

2nd=10, 3rd=5, 4th=2), self-explain (n=21; 2nd=8, 3rd=8, 4th=5), or additional-practice (n=31; 2nd=16, 3rd=10, 4th=5). Although the proportion of students in each condition from each grade level was not the same, it was approximately equal, $\chi^2(4)$=1.949, p=.745. During the intervention, all students were taught a procedure for solving two mathematical equivalence problems and then worked through six or twelve practice problems. Answer feedback was given on all problems. Students in the self-explain condition were prompted to explain examples of correct and incorrect answers.

Materials

Intervention. The intervention problems were mathematical equivalence problems with a repeated addend on both sides of the equation. The initial two instructional problems had the unknown in the final position, and the practice problems alternated between the unknown in the final position or immediately after the equals sign (e.g. 6+3+4=6+__; 5+3+9=__+5). The six additional practice problems were isomorphic versions of the first six, maintaining the same equation structure but with different numbers. The intervention materials were presented on a computer using EPrime 2.0 software (2007).

Assessments. The pre-, post- and retention tests were paper-and-pencil and were previously develope Rittle-Johnson, Matthews, Taylor, & McEldoon, 2011). One version was used as the pretest, and an isomorphic version was used as the post and retention tests. The assessments had *conceptual knowledge* and *procedural knowledge* sections, as outlined in Appendix A. The conceptual section had two components: one focused on the meaning of the equals sign and the other tested students' knowledge of allowable equation structures (e.g. "Is 8=3+5 true or false?"). The procedural knowledge section contained learning items, which had the same equation structure as those in the intervention and could be solved using the instructed

procedure, and transfer items, which were similar but included either subtraction or a blank on the left and required adapting the instructed procedure - a standard measure of transfer (Atkinson et al., 2003; Chen & Klahr, 1999). Far transfer was assessed at retention test with 8 items intended to tap a higher level of conceptual thinking. However, performance was quite low and no differences were found across conditions, so this subscale was not considered further.

Procedure

Pretests were administered on a whole-class basis and took 30 minutes to complete. Students identified as struggling with mathematical equivalence participated in a one-on-one intervention session with an experimenter a few weeks later. The intervention lasted about 50 minutes, and consisted of instruction, problem solving with or without self-explanation prompts, and an immediate post-test. The session was conducted by one of three female experimenters in a quiet room of the school. All students received instruction on an add-subtract procedure for solving two math equivalence problems. Instruction on this procedure supports learning and does not interact with self-explanation prompts (Rittle-Johnson, 2006). Students were taught to add together the three numbers on one side of the equals sign and subtract the number on the other side. Students were then presented with six or twelve problems, depending on condition. All students solved each problem and then provided a verbal procedure report. Procedure reports do not influence accuracy or procedure use, as it is merely an immediate report of working memory contents (Chi, 2000; McGilly & Siegler, 1990; Siegler & Crowley, 1991; Steffler, Varnhagen, Friesen, & Treiman, 1998). All were told their numeric answer was correct or were told the correct answer. See Figure 1.1 for an example screenshot. Children in the control and additional-practice conditions then moved to the next problem.

In the self-explain condition, after accuracy feedback, students were presented with correct and incorrect examples of the problem they just solved, and were told, "I showed this problem to some students at another school, and [Jenny] got [19], which is a wrong answer. [Allison] got [7], which is the right answer." (Figure 1.2). The incorrect example contained an answer that resulted from incorrect procedures students typically use. The students were asked to consider the procedure the hypothetical student used (e.g. "Tell me HOW you think Allison got 7, which is the right answer?") and prompted why the answers were correct or incorrect (e.g. "WHY do you think 7 is the right answer?"). Both the how and why prompts were included to encourage students to think about how to solve the problem and why that procedure was correct or incorrect. Students explained correct and incorrect examples because explaining both types of examples leads to better learning compared to explaining only correct examples (Siegler, 2002), and we wanted to provide students with optimal examples for self-explanation. This design has been used in several prior studies of the effect of self-explanation on mathematical equivalence (Matthews & Rittle-Johnson, 2009; Rittle-Johnson, 2006; Siegler, 2002).

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Figure 1 - Screenshots of Intervention.

Screenshot of Problem-Solving (1.1) and of Self-Explanation prompt (1.2)

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After the intervention, students completed a backward digit span task to measure their working memory capacity, as a metric for general processing ability (Wechsler, 2003), and an immediate posttest. A 30-minute retention test was administered on a whole-class basis an average of two weeks after all students in each class completed the intervention session.

Time on task during intervention was recorded and evaluated. As expected, the control condition took much less time ($M=6.3$ minutes, $SD=1.6$) than the self-explain ($M=14.3$ minutes, $SD=4.7$) and additional-practice ($M=12.0$ minutes, $SD=4.2$) conditions. Despite efforts to keep intervention time equal, students in the self-explain condition took longer than the additional-practice condition, $F(1,66)=4.31$, $p=.042$, $\eta_p^2=0.061$. Exploratory analyses suggested that time-on-task did not account for differences in outcomes between the two conditions.

Coding

Assessments. The assessments were scored according to criteria listed in Appendix A. Internal consistency, as assessed by Cronbach's alpha, was good for the primary scales and acceptable for the subscales, and was sufficient for group comparisons (Thorndike, 2005) (see Appendix A). An independent coder coded 20% of all student work. Kappa coefficients for interrater agreement ranged from 0.83 to 1.00, indicating substantial agreement (Landis & Koch, 1977).

Intervention Explanations. Recall that only students in the self-explanation condition provided explanations during the intervention. Their explanations were coded for quality. First, their "how" explanations for the correct answers were coded to identify whether students could infer a correct procedure, as described in Table 1.

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Table 1 – "How" Explanation Coding

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Next, students' "why" explanations were coded into 5 categories: (1) Procedural explanations explicitly referenced specific procedure steps with no other rationale (e.g., "Because um 3+4+8-8 is 7."), (2) conceptual explanations referred to the need to make the two

sides equal (e.g., ''7 is the right answer because 8+7=15 just like 3+4+8=15.''), (3) answer explanations simply referred to the answers shown in the examples, (4) others were vague or nonsense responses, and (5) other nonresponses (e.g., "I don't know."). Kappa coefficients for interrater agreement on 20% of explanations were .94 for "How" prompts and .78 for "Why" prompts.

Data Analysis

Our hypotheses were tested using ANCOVA models with three planned contrasts. The first contrasted the self-explain and control conditions to test for an effect of explaining over the same amount of practice (hypothesis 1). The second contrasted the self-explain and additional-practice conditions to test whether self-explanation was better than an alternative use of time (hypothesis 2). The third contrasted the additional-practice and control conditions to test for an effect of additional practice (hypothesis 3). Because we had specific hypotheses, we used planned contrasts rather than omnibus tests for condition, as recommended by an APA statistical task force (Wilkinson et al., 1999). To control for prior knowledge and general processing ability, students' pretest conceptual and procedural knowledge and backward digit span scores were covariates in all models. Grade was not included in the model because grade was never a strong predictor of performance, F's<2. We report effect sizes and observed power because they should be considered when interpreting the practical significance of results, and relying too heavily on p-values may lead to misguided interpretations (Hubbard & Lindsay, 2008; Sterne & Davey-Smith; 2001). Observed power is the probability of achieving significance given the sample size and presuming the effect size is true of the population (O'Keefe, 2007). Especially when sample and effect sizes are low, limited power can be a rival explanation of statistically

non-significant findings, and one must be careful not to falsely reject the alternative hypothesis (Onwuegbuzie & Leech, 2004).

Results

We first discuss students' performance at pretest. We follow this with a report of the effects of condition on conceptual and procedural knowledge at post and retention test. Finally, we briefly report on the quality of self-explanations students generated during the intervention.

Pretest Knowledge

At pretest, the conditions were similar in age (*M*=8.8, *SD*=0.82), average grade level, (*M=2.7, SD=0.76),* backwards digit span (*M*=4.5, *SD*=1.2), and IOWA standardized national percentile rank scores in math (*M*=57.4, *SD*=24.5) and reading (*M*=61.7, *SD*=23.4), with no differences between conditions, *F*'s<0.95. The conditions were also similar in pretest scores (Table 2). There were no differences in overall conceptual or procedural knowledge, nor differences on most of the subscales, *F*'s<2.97. The one exception was that the additional-practice condition had higher scores on the subscale of procedural transfer than the control condition, $F(1,66)=7.8$, $p=.007$, $\eta_p^2=.106$, Obs. Power=.787.

Effects of Condition on Outcomes

The effects of condition on conceptual and procedural knowledge outcomes were examined using repeated measures ANCOVA models, with post and retention test scores as dependent measures. All following results use this model. We did not expect differences based on assessment time, and analyses indicated that there were no effects of assessment time, *F's*<0.86, or interactions between assessment time and condition in any analyses, *F's*<1.7. See Table 2 for all assessment scores by condition and Table 3 for ANCOVA results for the planned contrasts and covariates. Note that the assumption of homogeneity of variance was met for all

analyses, as tested with Box's test of equality of covariance matrices that accounted for repeated measures and covariates, *F's*<1.8.

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Table 2 - Assessment Items Correct by Condition

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Table 3 - Analysis of Covariance Results

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Effects of Condition on Conceptual Knowledge

Students in the self-explain condition generally had higher conceptual knowledge scores than students in the other two conditions at posttest and retention test. The ANCOVA results indicated that the self-explain condition outperformed the control condition on the conceptual knowledge measure, but was not reliably better than the additional-practice condition (Table 3). Though the additional practice condition had slightly higher scores, there were only minimal differences relative to the control condition.

To better understand this effect, we considered conceptual knowledge of the equal sign and equation structures separately. There were no differences between conditions in equal sign knowledge, F's<0.52. Rather, the conditions differed in knowledge of equation structures, with the self-explain condition performing best; outperforming the control, $F(1,63)=10.59$, $p=.002$, $\eta_p^2=.144$, Obs. Power=.893, and additional-practice conditions, $F(1,63)=3.63$, $p=.061$, $\eta_p^2=.054$, Obs. Power=.467. The additional practice students also scored slightly higher than the control condition, $F(1,63)=2.88$, $p=.095$, $\eta_p^2=.044$, Obs. Power=.386.

Effects of Condition on Procedural Knowledge

Students in the self-explain condition performed highest on the procedural knowledge measure, followed closely by the additional practice condition. The self-explain condition performed better than the control condition, and there were no other differences between conditions (Table 3).

Because we expected differences to be stronger for procedural transfer, we considered procedural learning and transfer separately. For procedural learning, the additional practice condition had the highest scores, followed by the self-explain and then the control conditions. The self-explain condition did not differ from the control or additional-practice conditions in procedural learning, F's<2.4. The additional-practice condition had slightly higher scores than the control condition, $F(1,63)=3.25$, $p=.076$, $\eta_p^2=.049$, Obs. Power=.427.

On the procedural transfer items, the self-explain condition performed somewhat better than both the control, $F(1,63)=3.91$, $p=.052$, $\eta_p^2=.058$, Obs. Power=.495, and additional-practice conditions, $F(1,63)=3.53$, $p=.065$, $\eta_p^2=.053$, Obs. Power=.457. There were no differences between the control and additional-practice conditions on transfer items, $F<0.13$.

Self-Explanation Quality

Recall that students were prompted to explain both how a student might have gotten an example answer and why that answer was correct or incorrect. Self-explanation students' how explanations for correct answers indicated that students were able to describe a correct procedure on about 75% of trials, with students predominantly describing the add-subtract procedure, which we had taught them (Table 1). Experience describing correct problem solving procedures may be beneficial for learning. Frequency of describing a correct procedure was positively correlated with conceptual knowledge (post: $r_b=.66$, $p=.001$; retention: $r_b=.51$, $p=.019$); which consists of knowledge of the equal sign (post: $r_b=.66$, $p=.001$; retention: $r_b=.51$, $p=.019$) and

equation structures (post: r_b=.66, p=.001; retention: r_b=.51, p=.019). This relationship also held

for procedural transfer at retention (r_b=.39, p=.079).

When answering why an answer was correct or not, students often talked about

procedures (57% of explanations), sometimes focused on the answer (16%), and rarely directly

mentioned equivalence concepts (6%). Students also referred to other reasons that were vague or

unintelligible (10%), or reported that they did not know (11%). There were no differences in

quality when discussing correct and incorrect answers, and there were no strong relationships

between frequency of a particular explanation type and assessment scores. Overall, students

typically described procedures to justify why an answer was correct or incorrect.

Summary

Relative to the control condition, the self-explain condition supported greater conceptual

knowledge, particularly of equation structures, and greater procedural knowledge, particularly

for procedural transfer. However, relative to additional-practice, the self-explain condition had

modest benefits. The two conditions did not differ greatly on any measure, although the self-

explain condition tended to have greater knowledge of equation structures and procedural

transfer. Finally, although the additional-practice condition tended to have higher scores, it did

not support much greater knowledge relative to the control condition. Students' self-explanations

indicated that they were often able to describe a correct solution procedure when asked how to

find the correct answer and continued to focus on procedures when asked why an answer was

correct or incorrect. In turn, frequency of describing correct procedures was related to

knowledge of equation structures and procedural transfer.

Discussion

Prompting elementary-school children to explain how and why example solutions were correct or incorrect improved their knowledge of mathematical equivalence relative to having them solve the same number of problems. However, the benefits were not as strong relative to an alternative activity that made time on task more comparable - solving additional problems. Our self-explanation manipulation was typical of the self-explanation literature in problem-solving domains (e.g., Calin-Jageman & Ratner, 2005; de Bruin et al., 2007; Matthews & Rittle-Johnson, 2009). Unlike most prior studies, we investigated the benefits of self-explanation prompts against a control group with the same amount of problem-solving experience and against an alternative use of the time required to self-explain. Findings indicate that greater attention needs to be paid to how much self-explanation prompts offer advantages over alternative uses of time.

Self-Explanation as an Additional Versus Alternative Activity

First, consider the benefits of self-explanation prompts when included as an additional activity to complete when solving problems. In line with past research, self-explanation prompts increased knowledge relative to comparable problem-solving experience. We found a benefit for conceptual knowledge, similar to prior findings with student teachers learning geometry (Hilbert et al., 2008) and undergraduates learning probability (Berthold & Renkl, 2009). The current study extends these findings to younger children in a less complex domain. It is the first to document increases in conceptual knowledge from self-explanation prompts in a problem-solving domain before adolescence, suggesting prompts can support understanding in children. In addition to supporting conceptual knowledge, self-explanation prompts had benefits for procedural knowledge, particularly for procedural transfer, in line with past studies (Berthold et al., 2009; de Bruin et al., 2007; Große & Renkl, 2007; Rittle-Johnson, 2006).

The benefits of self-explanation prompts over an alternative use of time were smaller and less reliable. The self-explanation students consistently scored higher than the additional-practice students, although the differences were only of note for two subscales and did not reach traditional levels of significance. However, our self-explain condition supported notably greater learning than the control condition, whereas the additional-practice condition rarely did. Further, there were two specific advantages of self-explanation prompts over additional practice.

First, self-explainers were more successful on the conceptual equation structure items. One reason for this may be that prompts to figure out how to find the correct answer increased awareness of problem structure, especially the position of the equal sign and the presence of operations on both sides of it. For example, the add-subtract procedure requires noticing when to stop adding numbers (at the equal sign) and the presence of numbers after the equal sign. Indeed, frequency of being able to describe a correct procedure was correlated with success on the equation structure items. This is in line with the hypothesis that self-explaining increases learning by repairing and enriching existing knowledge to make it better structured (Chi, 2009; Fonseca & Chi, 2010). Second, the self-explainers had better procedural transfer than the additional-practice condition. Again, this may be due in part to self-explainers spending additional time talking about correct procedures during the intervention. Indeed, procedure generalization is a proposed mechanism of self-explanation (Calin-Jageman & Ratner, 2005; Rittle-Johnson, 2006).

Additionally, the self-explanation condition may have led to better performance because students self-explained correct and incorrect examples. Reflecting on correct and incorrect examples can help students recognize critical features of examples and what makes incorrect examples wrong (VanLehn, 1999). By engaging conflicting ideas, students may be motivated to

think more deeply about concepts (Durkin & Rittle-Johnson, 2012; Van den Broek & Kendeou, 2008). Across all conditions, most students were exposed to correct and incorrect examples because they solved some problems incorrectly and were told the correct answer; however, only students in the self-explain condition were prompted to reflect on correct and incorrect examples.

The findings suggest some small, unique benefits of self-explanation relative to an alternative use of time. At the same time, it is important to consider potential benefits of this alternative - supporting additional practice, particularly on unfamiliar problems. Both activities are constructive learning activities, as they each require responses that go beyond what is provided in the original material (Chi, 2009; Fonseca & Chi, 2010). Both the self-explanation prompts and additional practice provided more opportunities for thinking about correct procedures (describing or implementing them) than the control condition. In turn, this should strengthen a procedure's memory trace and related relevant knowledge, increasing the likelihood that the procedure will be selected in the future (Ericsson et al., 1993; Logan, 1990). Consequently, self-explanation prompts and additional practice can both provide opportunities for students to improve their knowledge, although there may be some benefits specific to self-explanation prompts.

Limitations and Future Directions

Because it is much easier to implement additional practice than self-explanation prompts, the relative benefits of these activities merit additional research. The results of this study would be strengthened and more conclusive if replicated with a larger sample. The benefits of prompting for self-explanation may also be more substantial when learners have more time to utilize the technique. Our intervention lasted about 15 minutes. The benefits of self-explanation prompts relative to additional practice could accumulate over time. It is also possible that the

strength of our condition manipulation was weakened because all conditions provided procedure reports. Reporting procedure use is a direct report of working memory and does not influence procedure use (e.g. McGilly & Siegler, 1990). Nevertheless, procedure reports may have promoted some reflection that was redundant with self-explanation. Further, it is important to test whether our findings would generalize to self-explanations that only involved correct examples.

Additionally, future research should incorporate supports to improve explanation quality. Prompting for self-explanation is thought to be beneficial for learning regardless of explanation quality (Chi, 2000), but self-explanation prompts should be more effective when learners can provide substantive explanations. For example, providing explanation sentence frames for the student to complete and training and feedback on explanation quality have been shown to benefit learning (Aleven & Koedinger, 2002; Berthold et al., 2009; Bielaczyc et al., 1995). Providing more support for explanation may be particularly relevant for young learners or those with low prior knowledge, as our learners were. Future research should compare scaffolded self-explanation to alternative uses of time, such as additional practice.

Conclusion

Prompts to self-explain benefited conceptual and procedural knowledge relative to comparable problem-solving experience, but self-explanation prompts had more modest benefits relative to solving additional problems. The findings suggest that self-explanation prompts have some small unique learning benefits, but that greater attention needs to be paid to how much self-explanation offers advantages over alternative uses of time.

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Table 1

"How" Explanation Coding

Strategy	Mean % Use *(SD)*	Definition	Example for: $4 + 5 + 8 = \_ + 8$
Total Correct Strategy Use	74% *(33%)*		
Equalizer	6% *(16%)*	Sets up the two sides as equal	"He added 4 plus 5 plus 8, and got 17, and thought about what 8 plus what equals 17, and got 9."
Add Subtract	66% *(36%)*	Sums one side of the equation and subtracts the number on the other	"She added 4 5 and 8 and got 17 and subtracted 17 and 8 and got 19."
Grouping	2% *(5%)*	Sums two numbers on left side that are not repeated on the right side	"He probably just added the 4 and the 5."
Total Incorrect Strategy Use	26% *(33%)*		
Incomplete Procedure	8% *(11%)*	Uses both numbers and operations, but procedure unclear	"because the... because 5 plus 8, is 13, so it makes…um, 9 automatically goes in her brain whenever it's like that"
Vague	13% *(26%)*	Unable to describe a	"Umm… she didn't count too low and didn't count too high."

procedure; vague

| Don't Know | 5%
(15%) | The student doesn't know | "I don't know" |

Is Self-Explanation Worth the Time? A Comparison To Additional Practice

Table 2

Assessment Items Correct by Condition

Assessment Component	Time	Control		Self-Explanation		Add'l Practice	
		M	*SD*	*M*	*SD*	*M*	*SD*
Conceptual	Pretest	5.24	*3.35*	5.24	*2.72*	6.10	*3.04*
Knowledge	Posttest	6.18	*3.50*	7.81	*3.46*	6.90	*3.11*
(15 items)	Retention	6.35	*3.76*	7.81	*3.64*	7.84	*3.13*
Equals	Pretest	1.94	*1.71*	2.33	*1.65*	2.16	*1.49*
sign	Posttest	2.82	*1.85*	2.95	*1.80*	2.74	*1.81*
(6 items)	Retention	2.88	*1.73*	2.95	*1.69*	3.00	*1.88*
	Pretest	3.29	*2.23*	2.90	*2.00*	3.94	*2.13*
Structure	Posttest	3.35	*2.23*	4.86	*2.15*	4.16	*2.00*
(9 items)	Retention	3.47	*2.43*	4.86	*2.41*	4.84	*1.99*
Procedural	Pretest	1.53	*1.55*	2.05	*2.06*	2.39	*1.80*
Knowledge	Posttest	3.12	*2.55*	4.57	*2.94*	4.32	*2.48*
(8 items)	Retention	3.12	*2.93*	4.86	*2.71*	4.26	*2.99*
Procedural	Pretest	1.00	*1.17*	1.24	*1.41*	1.06	*1.15*
Learning	Posttest	1.29	*1.16*	1.76	*1.22*	2.00	*0.97*
(Pre: 4, 3)	Retention	1.12	*1.22*	1.81	*1.25*	1.81	*1.30*
Procedural	Pretest	0.53	*0.62*	0.81	*0.93*	1.32	*1.08*
Transfer	Posttest	1.82	*1.55*	2.81	*1.94*	2.32	*1.89*
(Pre:4, 5)	Retention	2.00	*1.87*	3.05	*1.60*	2.45	*1.95*

Note. The pretest contained 4 procedural learning and 4 transfer items. The post and retention tests contained 3 learning and 5 transfer items.

Table 3

Analysis of Covariance Results for Learning Outcomes

Assessment Component	Conceptual				Procedural			
	F	p	η^2	Obs. Power	F	p	η^2	Obs. Power
Self-Explain vs Control	4.343	.041	.064	.537	3.778	.056	.057	.482
Self-Explain vs Add'l Practice	2.547	.115	.039	.349	1.165	.285	.018	.186
Add'l Practice vs Control	0.546	.463	.009	.112	1.138	.290	.018	.183
Conceptual Pretest	41.77	.000	.399	1.00	3.014	.087	.046	.401
Procedural Pretest	1.034	.313	.016	.170	5.928	.018	.086	.669
Backwards Digit Span	4.514	.038	.067	.553	1.467	.230	.023	.222

Note. All degrees of freedom are (1,63).

Figure Captions

Figure 1. Screenshots of Intervention. Screenshot of Problem-Solving screen (1.1) and screenshot of Self-Explanation prompt screen (1.2)

Figure 1

(1.1)

$6 + 3 + 4 = 6 + \boxed{13}$

How did you get your answer?

7 is the correct answer.

(1.2)

Jenny got 19 which is a wrong answer

$6 + 3 + 4 = 6 + \boxed{19}$

Allison got 7 which is the right answer

$6 + 3 + 4 = 6 + \boxed{7}$

Appendix A

Assessment Items and Scoring Criteria

Component	Items	Coding
Conceptual Knowledge *Cronbach's α: Post=.76, Reten=.79*		
Meaning of the Equals Sign *α: Post=.72, Reten=.72*	1) What does the equal sign (=) mean? Can it mean anything else?	1 point if defined relationally at any time (e.g., "same on both sides")
	2) Which of these pairs of numbers is equal to 6+4?	1 point if selects '5+5'
	3) Which answer choice below would you put in the empty box to show that five cents is the same amount of money as one nickel?	1 point if selects '='
	4) Is "The equal sign means the same as" a good definition of the equal sign?	1 point if selects 'good'
	5) Which is the best definition of the equal sign? The equal sign means the same as, The equal sign means add, or The equal sign means the answer to the problem.	1 point is selects 'The equal sign means the same as'
	6) In this statement: 1 dollar=100 pennies, What does this equal sign mean?	1 point if defined relationally
Structure of Equations *α: Post=.66, Reten=.71*	7) Encoding: Reproduce three equivalence problems, one at a time, from memory after a 5-s delay	1 point for each problem reproduced with the correct structure (numeral, operations and equal sign in correct place).
	8) Judgment: Judge if four non-standard problems 'make sense' or not (e.g., 5+3=3+5; 6=6+0)	1 point for each problem correctly judged as 'true'

	9) Judge and Explain: Judge if two equivalence problems 'make sense' or not, and explain how they know	If student judges as 'true', and notes that both sides have the same sum or same value, or that inverse is true; 1 point for each problem
Procedural Knowledge *α: Post=.83, Reten=.88*		
Procedural Learning *α: Post=.63,* *Reten=.81*	10) 3 equivalence problems similar to intervention problems (e.g., 3+4=□+5; 7+6+4=7+□)	1 pt each if used a correct procedure[a]
Procedural Transfer *α: Post=.79,* *Reten=.79*	11) 5 equivalence problems with unfamiliar problem features (e.g., □+6=8+5+6; 8+5 - 3=8+□)	1 pt each if used a correct procedure

[a] Accuracy measured by correct procedure use and by numeric accuracy of the answer were very similar and highly correlated ($r=.95$).