Comparing and Discussing Multiple Strategies to Promote Learning in Mathematics Classrooms

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Comparison is a powerful learning process. How can we can use comparison to support better learning of school mathematics within classroom settings? In 5 short-term experimental, classroom-based studies, we evaluated comparison of multiple strategies for supporting mathematics knowledge. We next developed supplemental Algebra I curriculum and professional development for teachers to integrate Comparison and Explanation of Multiple Strategies (CEMS) in their classrooms and tested the promise of the approach. Benefits and challenges emerged, leading to evidence-based guidelines for effectively supporting comparison and explanation in the classroom.

Students too often memorise ideas without understanding the ideas or being able to flexibly apply them to new contexts. For example, only 11% of 15-year-olds from around the world could work strategically using well-developed thinking and reasoning skills to solve math problems (OECD, 2016). Cognitive science research provides many insights into potential ways to improve teaching and learning in schools, but those insights infrequently make their way into classrooms (National Academies of Sciences, 2018). In the current paper, we focus on our efforts to understand how one basic learning process, comparison, can be harnessed to improve mathematics learning in schools.

We often learn through comparison. For example, we compare different brands and models of products, we compare one treatment option to another, and we compare new words, objects and ideas to ones we already know. These comparisons help us recognise what features are important and merit more attention, which can lead to deeper learning (Gentner, 1983). Indeed, research indicates that comparison promotes learning across a range of topics, including math, science and language (Alfieri et al., 2013).

In mathematics education, comparison of multiple solution strategies is a recommended instructional method in countries throughout the world (Australian Education Ministers, 2006; National Council of Teachers of Mathematics, 2014; Shimizu, 1999). Teachers are encouraged to have students share, compare and discuss multiple strategies for solving a particular problem (e.g., discuss the similarities and differences in the strategies). This recommendation is based on observations that expert teachers in countries such as the U.S. and Japan sometimes have students engage in this process, which is thought to promote deeper understanding and flexibility (Ball, 1993; Lampert, 1990; Shimizu, 1999).

However, observations in math classrooms suggest that many teachers are limited in the frequency and effectiveness with which they use comparison. In one study in the U.S., students were exposed to multiple strategies in 38% of observed algebra lessons, but teachers or students explicitly compared the strategies in only 9% of lessons (Star, Pollack, et al., 2015). Thus, research-based guidelines and curricula materias are needed to help teachers effectively use comparison.

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Research Summary

Research on engaging in comparison to promote mathematics learning in the past 15 years has revealed new insights about what, when and how to compare. In this research, target learning outcomes were procedural knowledge (i.e., knowledge of what actions to take to solve problems, such as equation solving procedures), procedural flexibility (i.e., knowledge of multiple procedures and when to use each), and conceptual knowledge (i.e., knowledge of abstract and general principles, such as equivalency) (Star et al., 2016). Conceptual and procedural knowledge are typically the focus of mathematics instruction and assessment, while procedural flexibility is not, despite evidence that procedural flexibility is an important component of mathematics expertise (Star, 2005).

We have conducted extensive research to develop and evaluate the effectiveness of using a comprehensive Compare and Discuss instructional routine to deepen learning of algebra, overviewed here and reported in detail elsewhere (see also Durkin et al., 2017; Rittle-Johnson et al., 2017; Star et al., 2016). We only report results that were statistically significant.

In our initial research, we redesigned 2–3 math lessons on a particular topic and researchers implemented these lessons during students' mathematics classes (e.g., Rittle-Johnson & Star, 2007, 2011; Star et al., 2016). Across five studies, with hundreds of students, those who compared strategies gained greater procedural flexibility, often gained greater procedural knowledge, and sometimes gained greater conceptual knowledge (for study details, see Rittle-Johnson & Star, 2007, 2009; Rittle-Johnson et al., 2009, 2012; Star & Rittle-Johnson, 2009). In one study, comparing strategies was more effective for students who were familiar with one of the strategies than students who were not (Rittle-Johnson et al., 2009). To address this potential limitation of asking students with limited prior knowledge to compare strategies, we gave students more time to learn a smaller amount of material. With this added support, comparing strategies immediately supported greater procedural flexibility than delaying exposure to multiple strategies, with or without comparison of the strategies, for all students (Rittle-Johnson et al., 2012). In large part because of our research, Educator's Practice Guides from the U.S. Department of Education identified comparing multiple solution strategies as one of five recommendations for improving mathematical problem solving (Woodward et al., 2012) and teaching students to intentionally choose from alternative algebraic strategies when solving problems for improving algebra knowledge (Star, Caronongan, et al., 2015).

Given the promise of the Compare and Discuss method to promote math learning, we created the Compare and Discuss Multiple Strategies (CDMS) for Algebra materials and professional development. We then refined and evaluated this method in two large studies with teachers.

First, to help teachers use comparison more frequently and effectively in their instruction, we have developed a Compare and Discuss instructional routine. We include discussion because it helps students articulate and reflect on what they have learned and supports deeper learning from comparison (Lampert, 1990; Stein et al., 2008; Webb et al., 2014). First, students compare two examples, making sense of each and identifying their similarities and differences. The examples are often two different strategies for solving the same problem. The first phase of instruction should focus on students comparing the two examples, identifying similarities and differences. Subsequently, students discuss key points about the comparison, such as when one is better than the other or what the similarities in the examples reveal about a general idea. At the end of the activity, the teacher summarises the main points of the comparison and discussion. An overview of our Compare and Discuss instructional routine is shown in Figure 1 and is also discussed in Rittle-Johnson and colleagues (2020). This instructional routine is useful for various instructional goals such as knowing multiple strategies and why and when to use them and revising incorrect strategies and misconceptions.

In our first teacher-led study, we conducted an initial evaluation of teachers' effective use of our CDMS method with 68 teachers who were randomly assigned to implement our CDMS approach or to continue using their existing curriculum and method across the school year (see Star, Pollack, et al., 2015). However, CDMS teachers used our materials much less often than requested (i.e., an average of 20 times, for about 4% of their math instructional time, with 30% of teachers using the materials 5 times or fewer). Coding of the videos indicated that teachers implemented the compare phase as intended, but they often did not support sustained class discussion. Some teachers were not comfortable leading discussions and provided little time for students to generate explanations in response to open-ended questions or to build on each other's ideas (Star, Newton, et al., 2015). At the end of the school year, students' algebra knowledge was not higher in classrooms in which our materials were available (based on over 1,600 students). Greater use of our comparison materials was associated with greater student learning, suggesting the approach has promise when used sufficiently often. These results indicated that teachers needed more support in their implementation of our CDMS instructional routine.

We then revised our approach to better support Algebra teachers in their frequent and effective use of CDMS. Figure 1 has an overview of the revised instructional routine. We incorporated a Think-Pair-Share instructional routine to better promote discussion and critical thinking. This includes a worksheet for students to record their ideas during each phase. We also provide teachers with additional support for the lesson summary. Finally, we provided ongoing professional development to the teachers, providing feedback on lessons they had implemented, how to improve their support of the routine and planning of when to use the routine.

In this second teacher-led study, 16 Algebra I teachers received professional development and supplemental materials to support CDMS when teaching a unit on linear equation solving and 475 of their students completed assessments of their linear equation solving knowledge before and after the unit (Durkin et al., 2021). Thirteen Algebra I teachers and their 359 students were the business-as-usual control group. CDMS increased how often teachers engaged their students in comparison of multiple strategies, sustained small group work, and sustained mathematical discussions. Students in CDMS classrooms also had higher knowledge of linear equations on the posttest, particularly procedural flexibility. Thus, encouraging teachers to regularly compare and discuss multiple strategies increased students' algebra learning.

Guidelines for Supporting Learning from Comparison

We recommend two phases to instruction: a compare phase and a discuss phase. We have developed evidence-based guidelines for each phase. In Figures 2 and 3, we provide examples of materials for the compare phase. All of our materials are available for download at https://www.compareanddiscuss.com/.

In the Compare Phase, it is important to:

1. Select two examples that have important similarities and/or differences (Markman & Gentner, 1993). When examples are too similar or too different, students focus on obvious, unimportant features of the examples which leads to unproductive discussions. The two examples can be prepared in advance or created by students. More than two examples can be used, but it may overwhelm students to compare them without considerable support.

2. Make the examples clear and visible. In math, worked examples (a problem and step-by-step strategy for solving it) are very effective examples to help novices learn new procedures and related concepts (Atkinson et al., 2000; Sweller & Cooper, 1985). They clearly lay out solution steps and are commonly included in textbooks, so they are familiar to students. They also provide a visual record of the solution steps. Verbal descriptions of multi-step processes or complex ideas, without visual aids, can be difficult for students to process because they have to both remember and make sense of the examples (Richland et al., 2007).
3. Use a variety of comparison types, matched to your instructional goals. We primarily use three types to support math learning:
   - *Which is better?* Examples are two correct strategies for solving the same problem, with the goal of learning when and why one strategy is more efficient or easier than another strategy for a given problem type (see Figure 2 for an example). This type of comparison promotes procedural knowledge and flexibility – knowledge of multiple strategies and when to use them (Rittle-Johnson & Star, 2007).
   - *Which is correct?* One example is correct and one is incorrect with the goal of understanding and avoiding common incorrect ways of thinking (see Figure 3 for an example). The examples can be a correct and an incorrect strategy or a naïve and expert perspective. Comparing correct and incorrect strategies supports gains in procedural knowledge, retention of conceptual knowledge, and a reduction in misconceptions (Durkin & Rittle-Johnson, 2012).
   - *Why does it work?* Examples are also two correct strategies for solving the same problem, but with the goal of illuminating the conceptual rationale in one strategy that is less apparent in the other strategy. This is in contrast to the Which is better? comparisons, where the goal is to learn when and why one strategy is better for solving particular types of problems. More frequent use of Why does it work? comparisons in the classroom is related to greater conceptual and procedural knowledge (Star, Pollack, et al., 2015).
4. When engaging in comparison, present both examples simultaneously, not one at a time. Students will make better comparisons because they do not have to rely on their memory of one example while comparing (Begolli & Richland, 2015; Gentner, 1983).
5. Present examples side-by-side and use gestures, common language (e.g., terms such as equivalent, factors, etc.) and other cues (e.g., highlight key parts in same color) to guide attention to important similarities and differences in the examples. For example, students were more likely to notice that the altitude of a triangle must pass through a vertex if they studied two examples next to each other, one an example of a triangle with an added red line that passed through a vertex and the other an example of the same triangle with an added red line that did not pass through the vertex (Guo & Pang, 2011). Without supports like these, students may fail to notice important features of the examples that are similar or different, (Marton & Pang, 2006; Namy & Gentner, 2002; Richland et al., 2007).
6. Prompt students to explain, preferably to a peer. First, prompt students to explain each example individually to be sure they understand each. Then, prompt students to compare the two, using both general prompts (e.g., »What are some similarities and differences between the two examples?«) and prompts focused on specific aspects of the examples to compare (e.g., »How is their first solution step different?«). Students can do this independently or with a peer, and we recommend students talking with a peer. Generating explanations improves students' comprehension and transfer (Chi, 2000; McEldoon et al., 2013), and talking with peers improves learning and communicative competence (Johnson & Johnson, 1994; Webb, 1991).

7. Provide additional support if both examples are unfamiliar to students. It is easier to compare an unfamiliar example to a familiar example, such as comparing a new strategy to a strategy students have already learned (Rittle-Johnson et al., 2009). Students can learn from comparing two unfamiliar examples, but it requires additional support, such as providing more time for the compare phase and providing carefully-crafted explanation prompts that guide students' attention towards key ideas (Rittle-Johnson et al., 2012).

In the Discuss Phase, it is important for teachers to:

1. Prompt students to reflect on key points about the comparison (i.e., discuss connections prompts), such as when one strategy is better than the other or what the similarities in the examples reveal about a general idea. Example prompts are: »On a timed test, would you rather use Alex's way or Morgan's way? Why?« and »Even though Alex and Morgan did different first steps, why did they both get the same answer?« Prompts to discuss connections encourage students to think critically about the examples and improve learning from comparison more than generic prompts to compare (Catrambone & Holyoak, 1989; Gentner et al., 2003). In addition, when teachers use more open-ended questions that prompt students to verbalise the main ideas of the lesson, students learn more (Star, Newton, et al., 2015).
2. Incorporate a Think-Pair-Share instructional routine to support high-quality discussion, communicative competence and critical thinking. First, students think on their own for a minute about the discuss connections prompt. Next, each student pairs with another student to discuss the prompt, summarising their ideas in writing. Then, students share their ideas in a whole class discussion. Teachers should call on multiple students to answer the same question and ask students to build on each other's ideas (e.g., »What do you think about Abbey's idea?«). Such classroom discussions promote critical thinking and improve student learning and communicative competence (Lampert, 1990; Stein et al., 2008; Webb et al., 2014).
3. Summarise the main points of the compare and discuss phases. Direct instruction on the key points supplements learners' comparisons and improves learning from comparison (Gick & Holyoak, 1983; Schwartz & Bransford, 1998; VanderStoep & Seifert, 1993). We recommend students then write a summary of the main points in their own words to be sure they understood and so they can practice communicating their ideas in writing.

Discussion

Comparison is a powerful learning process. In problem-solving domains such as mathematics, comparing multiple strategies promotes conceptual knowledge, procedural knowledge and/or procedural flexibility. However, comparison requires substantial mental effort by learners, and learners can become overwhelmed by it without adequate support, especially if all of the material is unfamiliar. Supports, such as presenting examples side-by-side and using cues to guide attention to important similarities and differences in the examples, facilitate learning from comparison. To help teachers use comparison more frequently and effectively in their classrooms, curricular materials, well-specified instructional routines, and sustained professional development are likely needed. We have developed a CDMS instructional routine that is a highly structured but quite adaptable to a range of topics in mathematics.

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Figure 1

Overview of a Compare-and-Discuss Multiple Strategies Instructional Routine

<table>
<tr><th>Compare</th><th>Discuss Connections</th></tr>
<tr><td>Prepare to Compare

What is the problem asking?

What is happening in the first method?

What is happening in the second method?</td><td>Prepare to Discuss (think, pair)

How does this comparison help you understand this problem?

How might you apply these methods to a similar problem?</td></tr>
<tr><td rowspan="2">Make Comparisons

What are the similarities and differences between the two methods?

Which method is better?

Which method is correct?

Why do both methods work?

How do the problems differ?</td><td>Discuss Connections (share)

What ideas would you like to share with the class?</td></tr>
<tr><td>Identify the Big Idea

Can you summarize the Big Idea in your own words?</td></tr>
</table>

Figure 2

Sample Worked Example Pair (WEP) for a Which is Better? Comparison

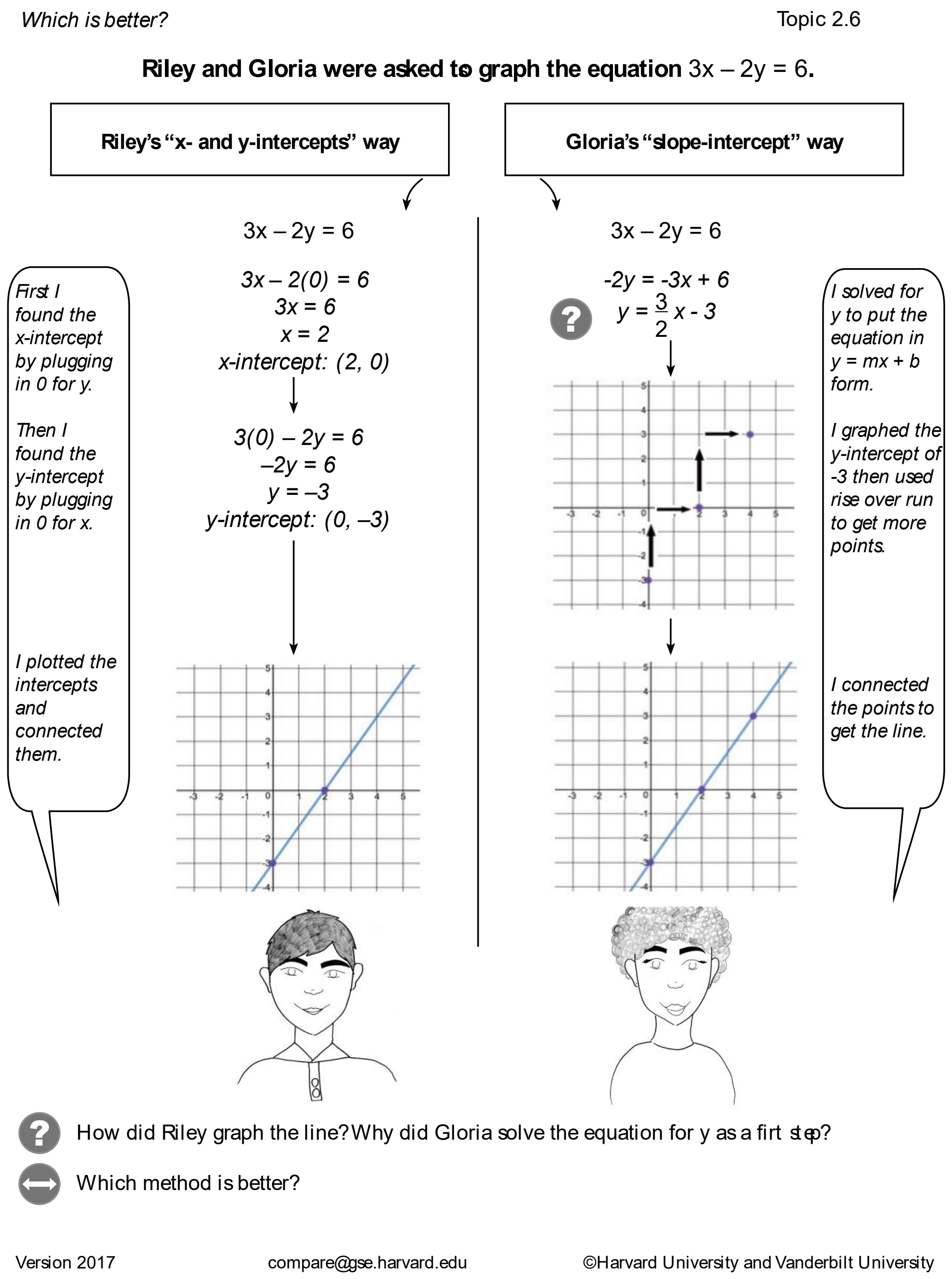

Figure 3

Sample Worked Example Pair (WEP) for a Which is Correct? Comparison