Analogical Scaffolding in Collaborative Learning

Soniya Gadgil (smg58@pitt.edu)
Timothy Nokes (nokes@pitt.edu)
Learning Research and Development Center
University of Pittsburgh
Pittsburgh, PA 15260 US

Abstract

Past research has shown that collaboration can facilitate learning and problem solving (e.g., Azmitia, 1988; Barron, 2000). In the current work, we compared the effects of three collaborative learning conditions: prompts that encourage analogical comparison between examples, prompts that guide sequentially studying single examples, and traditional instruction (practicing problem solving), as students learned to solve physics problems in the domain of rotational kinematics. Preliminary results showed a significant problem type by condition interaction effect.

Keywords: analogy; collaborative learning; comparison; problem solving; transfer

Introduction

Analogical comparison can be a powerful mechanism of learning from examples (e.g., Gentner, Loewenstein, & Thompson, 2003). However, students often have difficulty making spontaneous analogical comparisons (Atkinson, Derry, Renkl, & Wortham, 2000). Recent research by Nokes & VanLehn (2008) has shown that providing prompts to encourage analogical comparison of worked examples improves students' performance especially on far transfer tests. The current research extends this work by exploring the effect of analogical prompts on collaborative learning. We hypothesize that analogical comparison will scaffold the cognitive processes of explanation and knowledge construction that underlie successful collaborative learning, thereby helping students learn more effectively while collaborating.

Much research on collaborative learning has shown that when students learn in dyads, they show better learning gains (at the group level) than working alone (e.g., Azmitia, 1988; Barron, 2000). Much of this research has focused on identifying the conditions that underlie successful collaboration such as the presence of conflict (e.g., Schwartz, Neuman, and Biezuner, 2000), adequate scaffolding of the collaborative interaction (e.g., Rummel and Spada, 2005), and group composition characteristics, such as aptitude, age, gender etc (e.g., Webb, 1982). For example, we know that the presence of cognitive conflict is an important variable underlying successful collaborative learning in particular contexts. Schwartz, Neuman, and Biezuner (2000) showed that when students with misconceptions distinct from each others' collaborated, they were more likely to learn compared to those with the same misconception, or without a misconception.

We also know that scaffolding (or structuring) collaborative interaction is often critical for achieving effective learning gains (see Lin, 2001 for a review). For example, Rummel and Spada (2005) conducted an experiment in which students learned to collaborate by studying an example of collaboration in the presence or absence of a collaboration script. Dyads that received a script showed an advantage in learning over those who received no scaffolding. This is consistent with other results that show that providing scripted problem solving activities (e.g., one participant plays the role of the tutor vs. tutee and then switch) facilitate collaborative learning compared to those who learned individually or in unscripted conditions (McLaren et al., 2007).

Hausmann, Chi, and Roy (2004) have identified three mechanisms that are at play during collaborative learning. The first is "other directed explaining" and occurs when one partner explains to the other how to solve a problem. The second is explanation through "co-construction" in which both partners equally share the responsibility of sense-making. Collaborators extend each others' ideas and jointly work towards a common goal. The third mechanism is "self-explanation" in which one partner is engaged in a knowledge-building activity for his or her own learning. Data from physics problem solving by undergrads showed that all three mechanisms are at play in learning to solve problems collaboratively. However, the former two are more beneficial to both partners while the third is only beneficial to the partner doing the self-explaining.

In the current work, we explored whether scaffolding collaborative interaction by the means of providing analogical prompts can help students learn more effectively. We hypothesized that analogical comparison will provide specific scaffolding to encourage other-directed explanation and knowledge co-construction compared to studying individual examples sequentially, thus ensuring that both partners benefit from the collaborative interaction.

To test these hypotheses, we conducted an in-vivo classroom experiment in which we had students collaborate under one of three conditions: 1) with comparison prompts (i.e., questions instructing participants to compare two examples), 2) with sequential prompts (i.e., the same questions targeted towards studying individual examples) and 3) without prompts (problem solving and reading expert solutions/ explanations). The results will help us understand whether analogical comparison can be an effective tool to scaffold collaborative interactions above and beyond traditional instruction.

Analogical Comparison Helps Schema Acquisition

Why would analogical prompts be helpful to students while learning collaboratively? Analogical comparison has been shown to be an extremely effective learning mechanism for individuals (e.g., Cummins, 1992). Analogies play an important role in schema acquisition. A problem schema is a knowledge organization of the information associated with a particular problem category. Schemas have been hypothesized to be the underlying knowledge organization of expert knowledge (Chase & Simon, 1973). One way in which schemas can be acquired is through analogical comparison (Gick & Holyoak, 1983). Analogical comparison operates through aligning and mapping two example problem representations to one another and then extracting their commonalities.

Research on analogy and schema learning has shown that the acquisition of schematic knowledge promotes flexible transfer to novel problems. Many researchers have found a positive relationship between the quality of the abstracted schema and transfer to a novel problem that is an instance of that schema (Gick & Holyoak, 1983). For example, Gick and Holyoak (1983) found that transfer of a solution procedure was greater when participants' schemas contained more relevant structural features. Analogical prompts will assist in identifying the relevant structural features, thereby improving schema acquisition.

Analogical comparison has also been shown to improve learning even when both examples are not initially well understood (Gentner Lowenstein, & Thompson, 2003). By comparing the commonalities between two examples, students could focus on the causal structure and improve their learning about the concept. Kurtz, Miao, and Gentner (2001) showed that students who were learning about the concept of heat transfer learned more when comparing examples than when studying each example separately. In summary, prior work has shown that analogical comparison can facilitate schema abstraction and transfer of that knowledge to new problems.

However, the role of analogies has not been extensively examined in collaborative settings. We hypothesized that successful collaboration will be supported and enhanced by prompts that encourage dyads to engage in analogical comparison when learning about new concepts and solving novel problems. Analogical comparison will act as a script to facilitate constructive learning processes such as identifying the critical features of the problem, abstracting a problem solving schema, relating the critical features to the abstract concept or principle, facilitating error-correction, and fostering self-explanations, other-directed explanations, and co-construction. In the current work, we examine how analogical comparison may help students learn better through collaboration.

Method

Participants

Seventy-two students from the United States Naval Academy (USNA) participated in the experiment as a part of their normal Introductory Physics I course. Three sections with 24 students each participated in the experiment. Thus, there were in all 36 pairs of students, with 12 dyads in each section.

Design

The design was a between subjects design with dyads of students randomly assigned to one of the three conditions: *compare (n =*24*)*, *sequential (n =* 24*)*, and *problem solving (n =* 24*)*. Participants in the *compare* condition received analogical comparison prompts, i.e., questions instructing them to compare across two worked examples. Participants in the *sequential* condition received the same worked examples with informationally equivalent questions that focused on studying of individual examples. Participants in the *problem solving* condition received the same worked examples, but were not given any prompts to aid studying of the worked examples.

Learning Materials and Procedure

The learning materials were presented in paper booklets. In the learning phase, students studied the worked examples the learning booklet in collaborative dyads. The first section was common to all conditions and consisted of written descriptions of each of the principles students would be learning about (e.g., angular velocity, tangential acceleration, radial acceleration). This was followed by the symbolic representations for the concepts and principles along with a few graphs illustrating those concepts.

The booklet for the *compare* condition consisted of four worked examples and two analogical comparison tasks. The examples were divided into two pairs of problems that used the same concepts and principles. Each worked example was a word problem with the step-by-step problem solution (see Table 1 for an illustration). Justifications for the steps were not provided and students were expected to work collaboratively to generate those explanations. The second example in each pair applied the same concepts and principles but in a different context (see Table 1, Example 2). The analogical comparison task that followed consisted of prompts designed to guide comparison between the two worked examples. Solutions to the analogical comparison prompts were provided after students attempted to answer the questions.

The booklet for the *sequential* condition consisted of the same four worked examples, but each worked example was followed by learning prompts that were designed to guide studying of that individual worked example. Similar to the compare condition, the worked examples were word problems with the step-by-step problem solutions (see Table 1 for an illustration). Justifications for the steps were not provided and students were expected to work collaboratively to generate those explanations. The prompts for the two examples were informationally equivalent to the

Table 1: Examples of the Learning Materials

Worked Example 1

The flywheel of a steam engine runs with a constant angular velocity of magnitude 150 rev/min. When the steam is shut off, the friction of the bearings and of the air brings the wheel to rest in 2.2h. Assume that the wheel was spinning counterclockwise, and that this is the positive direction.

a. What is the average angular acceleration of the wheel?

Givens: $\omega_{0z} = 150\, {}^{rev}\!/_{\min}$, $\omega_z = 0\, {}^{rev}\!/_{\min}$, $t = 2.2h$

Conversions:

$$\omega_{0z} = 150\frac{rev}{\min} \times \frac{2\pi rad}{1rev} \times \frac{1\min}{60s} = 15.71\frac{rad}{s}$$

Sought: α

$$\omega_z = \omega_{0z} + \alpha t$$

$$\alpha_z = \frac{(\omega_z - \omega_{0z})}{t}$$

$$\alpha_z = \frac{(0\, {}^{rad}\!/_{s} - 15.71\, {}^{rad}\!/_{s})}{2.2h}$$

$$\alpha_z = \frac{-15.71\, {}^{rad}\!/_{s}}{7920\text{s}}$$

$$\alpha_z = -0.0020\, {}^{rad}\!/_{s^2}$$

(b) How many rotations will the wheel make before coming to rest?

Sought: N (number of rotations)

$$\theta_z = \omega_{0z} t + \tfrac{1}{2}\alpha_z t^2$$

$$\theta_z = (15.71\, {}^{rad}\!/_{s})(7920s) + \tfrac{1}{2}(-0.0020\, {}^{rad}\!/_{s^2})(7920s)^2$$

$$\theta_z = 124423.2\text{rad} - 62726.4 rad$$

$$\theta_z = 61696.8 rad$$

$$\theta_z = 61696.8 rad \times \frac{1rev}{2\pi rad} = 9819.4 rev$$

Worked Example 2

The wheel of a unicycle is traveling at a constant angular velocity of 10.8 rad/s. The rider suddenly backpedals, and the wheel is brought to a stop in 0.800 s. Assume that the wheel was spinning counterclockwise, and that this is the positive direction.

a. What is the average angular acceleration of the wheel?

Givens: $\omega_{0z} = 10.8\, {}^{rad}\!/_{s}$ $\omega_z = 0\, {}^{rad}\!/_{s}$, $t = 0.800s$

Sought: α_z

$$\omega_z = \omega_{0z} + \alpha_z t$$

$$\alpha_z = \frac{(\omega_z - \omega_{0z})}{t}$$

$$\alpha_z = \frac{(0\, {}^{rad}\!/_{s} - 10.8\, {}^{rad}\!/_{s})}{0.800s}$$

$$\alpha_z = -13.5\, {}^{rad}\!/_{s^2}$$

b. What angle will the wheel rotate through before coming to rest?

Sought: θ_z

$$\theta_z = \omega_{0z} t + \tfrac{1}{2}\alpha_z t^2$$

$$\theta_z = (10.8\, {}^{rad}\!/_{s})(0.800s) - \tfrac{1}{2}(13.5\, {}^{rad}\!/_{s^2})(0.800s)^2$$

$$\theta_z = 8.64 rad - 4.32 rad$$

$$\theta_z = 4.32 rad$$

Sample Questions for Sequential Group

Worked Example 1:
1. How do you define angular acceleration?
2. Why is final velocity assumed to be zero?
3. How do we calculate angular displacement?

Sample Questions for Compare Group

1. For Part A, what is similar and different between the two problems? Specifically, what is different between their angular velocities and time periods? How do these affect angular acceleration?
2. For part B, what is similar and different between the two problems? How do the two results for number of rotations compare? Explain why any differences might occur.

prompts in the compare condition (See Table 1 for example questions). Solutions to the learning prompts were provided after students attempted to answer the questions. The worked example pair was followed by an isomorphic problem.

The booklet for the *problem solving* condition contained the same four worked examples, but had no prompts to guide studying from those examples. Again, justifications to steps were not provided and students worked collaboratively to make sense of the examples. Students in this condition received the two isomorphic problems (one after each worked example pair) like the other two conditions. In addition, to equate for time on task, they received two additional isomorphic problem-solving tasks, so that the total time spent by all conditions was exactly the same.

Students in all three conditions were first given 10 minutes to study the principles booklet individually. After this, dyads were given learning booklets based on the condition to which they were assigned. They were given 16 minutes for studying the first worked example pair and answering analogical comparison or sequential prompts depending on which condition they were in. Students in the problem solving condition did not have to answer any questions, and were therefore given an extra problem to solve. This was followed by an isomorphic problem common to all conditions, for which students were given 6 minutes to solve. After students attempted to solve the isomorphic problem, they were given the solution to that problem with 2 minutes to study the solution.

A second pair of worked examples followed, for which the dyads were given 18 minutes to study. Again, the problem solving group got an extra problem in lieu of answering compare or sequential prompts. This was followed by a second isomorphic problem common to all three conditions for which the dyads had10 minutes to solve. After students attempted to solve this problem, they were given the solution to that problem with 2 minutes to study each solution.

Test Materials and Procedure

The test phase of the experiment included an immediate and delayed assessment which students completed individually. The immediate test was administered directly after the learning phase, and the delayed assessment occurred when students complete their homework for rotational kinematics problems. The immediate post-test consisted of three tasks: multiple choice questions, problem solving tasks, and qualitative reasoning tasks. The delayed assessment looked at transfer measures such as performance on homework problems on the same topic and on a subsequent topic of rotational dynamics. Only results from the immediate assessment are reported here.

Multiple-Choice Questions. This assessment consisted of ten multiple-choice questions in which students were given a target statement and were required to choose the best answer. This task assessed students' conceptual understanding and qualitative reasoning (they were not asked to calculate quantitative solutions).

Problem Solving. This test consisted of two word problems. The first problem was an isomorphic problem to one of the worked examples but had a different cover story (i.e., scenario). This problem measured near transfer. The second problem assessed the same concepts, however it included extraneous values that were not needed to solve the problem. The task was to decide which formula applies and correctly map the values in the problem statement to the variables in the formula. These problems assessed both concept access (determining the correct equation) as well as procedural application (generating the correct answer). The problems were similar to those used in the class textbook and ones that they completed in their homework.

Open-Ended Questions. This test consisted of two *'what's wrong?'* questions and two open-ended qualitative reasoning questions. In the "what's wrong" questions students had to determine if a problem was solved correctly and generate an explanation that describes why the solution was correct or incorrect. In the open-ended qualitative reasoning questions, students had to provide a solution to the problem along with an explanation.

All participants were given a test booklet containing the three tasks. They were given 10 minutes to complete the multiple-choice task, 13 minutes for the problem-solving task, and 13 minutes for the open-ended questions task. The total time for the experiment was 1 hour and 40 minutes (10 minutes for the principles booklet, 54 minutes for the learning booklet, and 36 minutes for the test booklet).

Predictions

On questions tapping conceptual understanding, we expected the compare condition to perform better than the sequential condition, because the comparison process should highlight critical features and help abstract principles common across the problems. The sequential condition in turn should outperform the problem-solving condition.

On the problem-solving task, we expect to see an advantage for the problem-solving group on the isomorphic problem because it focuses on step-by-step near transfer learning, and the problem-solving condition received more practice solving problems than the two other groups. However, on the other problem in this task, which contained extraneous values and required students to determine the relevant values, we expected the compare condition to outperform the sequential and problem-solving conditions, because comparison promotes abstraction; highlights critical features, and application conditions. We did not expect to see a difference between sequential and problem-solving conditions on this measure, because neither of these engaged in these learning processes.

On the open-ended questions, we again expected to see the compare and sequential conditions outperform the problem-solving condition.

Results

The results are divided into two sections, learning and test. In the learning results, we examine the performance of students on the two isomorphic problems that they solved during learning, and the answers to the compare or sequential questions. This will help us determine how much students learned during the learning phase.

The test results look at performance of students on the three test measures. These measures will show whether students are able to apply what they learned to new problems.

Learning Results

During learning, students in all three conditions studied worked examples and solved isomorphic problems. The answers to compare questions and sequential questions were scored for students in those conditions. Students were given one point for every correct concept they mentioned while answering the analogical comparison questions in the compare condition or questions directed at studying individual examples in the sequential condition.

If we look at the percentage of questions answered correctly, the sequential group answered a significantly higher percentage of questions (M = 70.28%, SE = 5%) correctly over the compare group (M = 50.66%, SE = 6%); $F(1,22) = 5.60$, $p < 0.05$.[1] This suggests the possibility that the sequential group correctly encoded a greater amount of knowledge than the compare group. The reason that the sequential group could answer more questions correctly may be that the compare questions were inherently more difficult than the sequential questions, and caused a greater cognitive load. Indeed, past research has shown that cognitive load is an important determinant of successful analogical learning (Keane, Ledgeway, and Duff, 1994).

Next, we looked at the performance of the three groups on the isomorphic problems that they solved during learning.

[1] Only the compare and non-compare groups are included in this comparison, because the problem-solving group were not required to answer any questions during learning.

On the first isomorphic problem, the three conditions were not significantly different; F (2,33) = 0.88, *ns.* On the second isomorphic problem, the three conditions were marginally different; F (2,33) = 2.60, $p < 0.1$ and the effect was in a direction favoring the sequential group over the compare and the problem solving groups.

The superior performance of the sequential group ran counter to our predictions, but can be attributed to the fact that students in this condition answered more questions correctly during learning. This suggests that they encoded more correct knowledge components during the learning that enabled them to solve isomorphic problems more accurately.

Next, we see whether this translated into better performance by the sequential group on the test phase of the experiment.

High variation was observed in performance on the learning tasks, suggesting the possibility that individual differences would interact with learning outcomes. We are interested in testing the effectiveness of our intervention on test performance for when testing was successful. Therefore, we selected the best learners from each group by conducting a median split based on the learning scores (i.e., average scores on isomorphic problems from the learning phase). This was based on the assumption that there are some qualitative differences between learners who show high learning and those who show low learning during the learning intervention. This left us with six pairs in each group (high / low split for each condition).

Test Results

As described earlier, the test phase was divided into three sections: multiple-choice, problem solving, and open-ended questions. Next, we will describe the performance of the three conditions on each of these measures. Note that the test phase was administered individually; therefore all scores reported below are means of scores for individual students.

Multiple-Choice Test. Overall, all three conditions performed poorly on the multiple-choice questions. The overall mean was 3.82 (SE = 0.23) out of a total of ten points. There were no significant difference between conditions, F (2,69) = 0.05, *ns.*

Therefore, we shall focus only on the performance of High learners. Item analysis of the multiple choice questions shows that the high learners in the compare condition performed significantly better than the high learners in the sequential and problem solving conditions on five questions. An ANOVA showed a significant difference between the three conditions, in a direction favoring the compare condition, F (2,33) = 3.86, $p < 0.05$ (See Fig. 1 for means and standard errors). Consistent with our predictions this result shows more conceptual learning for the compare condition than the sequential and problem solving conditions. Contrasts revealed that the compare group was significantly different from the sequential group t (1,33) = 2.56, p < 0.05 and problem-solving group; t (1,33) = 2.22, p < 0.05 but the sequential and problem-solving groups were not significantly different; t (1,33) = -0.34, *ns.*

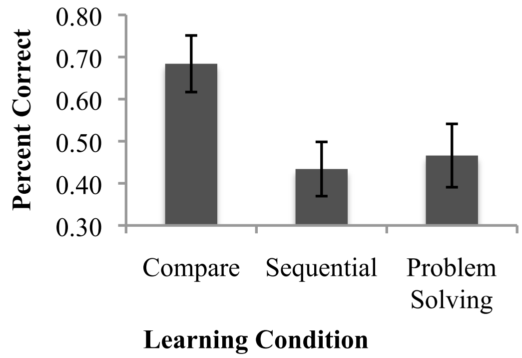

Figure 1: Performance of High learners on multiple-choice questions.

Problem Solving Test. The problem-solving test consisted of two questions, one of which was isomorphic to one of the problems the students had encountered in the learning intervention, but had different surface features. The other problem had extraneous values, which required students to determine which of the values were critical to solving the problem before they plugged in the numbers.

We conducted a mixed model repeated measures ANOVA with problem-type as the within subject factor, and condition as the between-subject factor. Again, consistent with our prediction, there was a significant interaction problem-type X condition interaction (F (2,33)=3.37, $p < 0.05$). (See Fig. 2) Specifically, the students in the compare condition and sequential conditions performed better on the extraneous information problems than on the isomorphic problems, whereas students in the problem solving condition performed better on the isomorphic problem than they did on the extraneous information problem. Students in the compare and sequential conditions acquired a better conceptual understanding with the help of the provided prompts, whereas those in the problem solving condition got no such scaffolding. However, they got more practice solving the same type of problems, thus explaining their better performance on the isomorphic problems.

Open-Ended Questions Test. The first question in this test consisted of two problems for which students had to determine whether the answer was correct or wrong and provide an explanation for the same. The second question consisted of two problems for which students had to calculate an answer and provide an explanation. Chi square tests revealed no difference between conditions on either question. All $\chi^2 s$ (2, N = 36) <4.8, *ns.*

Discussion

We had hypothesized that analogical prompts will provide better scaffolding for collaborative learning compared to prompts focused on single examples or no prompts. The

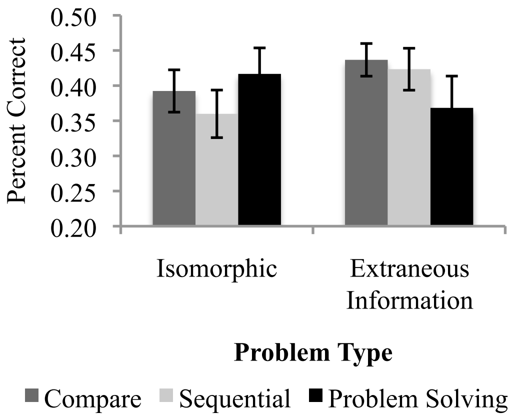

Figure 2: Problem-type by Condition interaction

findings from this experiment provide preliminary evidence that analogical comparison can support collaborative learning, particularly where conceptual understanding is required. We hypothesize that this is because the process of analogical comparison promotes abstraction; highlights schema and critical common features, and application conditions which gives an advantage to students in the compare condition.

We found significant differences in performance only for high learners. One potential reason that only half the students in the experiment showed good learning may be motivation. Perhaps, highly motivated students took the task seriously, and were able to learn from the intervention. Even within highly motivated learners, there was a benefit for doing analogical comparison over studying examples individually or practicing problem solving. However, an issue that future research should address is how we can get even the low learners to learn and what kinds of additional scaffolding we need to provide in order to help the low learners.

In order to understand what kinds of cognitive processes that led to learning, future work should undertake a fine-grained analysis of students' collaborative interactions. Further analysis will also look at long-term learning measures, such as performance on homework problems in rotational kinematics and a subsequent topic of rotational dynamics. This will help us understand whether our learning intervention had any effect on students' long- term retention and whether the knowledge they gained during learning could transfer to a related domain of rotational dynamics.

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