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Learning from collaborative problem solving: An analysis of three hypothesized mechanisms

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Abstract

It has been well established that collaborative learning is more effective in producing learning gains than individuals working alone. The present study investigates three potential mechanisms responsible for learning from collaborative problem solving: other-directed explaining, co-construction, and self-directed explaining. College undergraduates were trained to criterion on the first four chapters of a popular physics textbook. They were then asked to collaboratively solve three physics problems. Preliminary evidence suggests that other-directed explaining was effective in half of the cases, whereas co-construction led to proportionally more generated knowledge. Self-directed explaining was particularly effective for the individual generating the solution; however, there was only a modest gain for the partner who listened to the explanations. The relative impact of these three mechanisms is compared.

Introduction

Collaboration is a ubiquitous part of life and can be found in scientists' laboratories, the business world, the military, and the classroom. Given its usefulness in the real world, peer collaboration has become an important instructional intervention. The literature evaluating the effectiveness of peer collaboration has generally produced positive results (Dillenbourg, Baker, Blaye, & O'Malley, 1995); however, it is far from being an educational panacea (Barron, 2003). The open question remains, "Why is collaboration effective?" Prior research implicates three potential mechanisms responsible for learning during collaboration: other-directed explaining (Ploetzner, Dillenbourg, Praier, & Traum, 1999; Roscoe, 2003), co-construction (Damon, 1984; Rafal, 1996), and self-directed explaining (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, DeLeeuw, Chiu, & LaVancher, 1994). The goal of the present study is to investigate the relative contributions of all three mechanisms to individual learning.

The first mechanism, other-directed explaining, occurs when one peer instructs or explains to another partner how to solve a problem. Other-directed explaining may benefit only the speaker, but not the listener because the speaker is the one actively engaged in conveying the to-be-learned material (Chi, Siler, Jeong, Yamauchi, & Hausmann, 2001; Webb, Troper, & Fall, 1995). However, because both partners have opportunities to explain to their partners, it is conceivable that other-directed explaining is a mechanism that accounts for learning during collaboration.

The second hypothesized mechanism for successful learning from collaborative problem solving is co-construction. Co-construction is defined as the joint construction of knowledge. The process of constructing knowledge may proceed in a variety of ways, but the most natural is for peers to either elaborate or critically evaluate their partners' contributions.

Elaborative co-construction is the generation of knowledge by extending the ideas of one's partner (Tao & Gunstone, 1999) and has been shown to be an effective dialog pattern (Hogan, Nastasi, & Pressley, 1999; van Boxtel, van der Linden, & Kanselaar, 2000). Similarly, knowledge might be constructed through the critical discussion of ideas. Critical co-construction occurs when interacting peers critically evaluate each other's ideas. Support for this particular type of interaction comes from the literature on argumentation. Schwartz, Neuman, and Biezuner (2000) found dyads that successfully solved fraction problems were most likely to engage in argumentation.

Co-construction and other-directed explaining are likely candidates to explain the potential successes of learning from collaborative problem solving. However, there is another potentially overlooked mechanism, which is to learn from listening to someone self-explain (i.e., self-directed explaining). Learning from another person's explaining is analogous to learning from a worked-out example; however, in a collaborative problem-solving context, the source of the worked-out example is not a textbook, but a peer. When a dyad is faced with solving a problem, it is natural for one person to begin solving, while the other listens to the ensuing solution attempt (Shirouzu, Miyake, & Masukawa, 2002). The speaker may be talking out loud while solving a problem while her partner listens. This is a form of self-directed explaining. As has been shown in prior research, self-explaining is an effective learning strategy (Chi et al., 1989). What is unclear, however, is if a partner can benefit from listening to self-directed explaining. One goal of the present study is to provide initial evidence for the utility of self-directed explaining (or self-explaining with an audience).

The structure for the remainder of the paper is as follows. First, we will provide a brief description of the study, which

will then be followed by evidence for the three hypothesized mechanisms discussed above: other-directed explaining, co-construction, and self-directed explaining. The final section will compare the relative impact on learning from the three mechanisms.

Method

Participants

Students were recruited via advertisements placed in a university newspaper. The study used a between-subjects design with a total of ten undergraduate pairs ($n=20$) participating in the experimental group (i.e., Collaboration condition) and a total of ten ($n=10$) undergraduates in the control group (i.e., Text-only condition). Upon completion of the experiment, participants were paid for their time. To control for prior knowledge, eligible participants were required to have taken only one high school physics course.

Materials

The domain chosen for the present study was kinematics. Some of the topics covered were vector addition and subtraction, average and instantaneous velocity and acceleration, and an emphasis on Newton's second and third laws. The material was taken from the first five chapters of a popular physics textbook (Halliday & Resnick, 1981).

Measures Four mastery tests were developed to assess participants' understanding of each of the first four chapters. Participants were required to solve 80% of the problems correctly before advancing to the next chapter. After the first four chapters were learned to mastery, participants read the fifth chapter on force. The test administered after the participants had read the fifth chapter served as the pretest to the learning intervention.

The pretest consisted of three problems. The three problems were decomposed into a total of nine solution steps. Each solution step was then labeled with a concept from physics. For example, Problem 1 asks the individual to find the acceleration of two boxes in contact. To correctly solve the problem, the two boxes should be conceptualized as a *compound body*. To demonstrate an understanding of the compound body concept, the solver is required to sum the masses. The labeled solution steps will henceforth be called "concepts" (see Appendix for the mapping between problems, concepts, and the groups that were assigned to each problem). There were a total of nine different physics concepts across all three problems.

The text was available to the participants during the mastery tests, the pretest, and during the instructional phase, but it was not available during the posttest. The reason for making the text available during the pretest, but not the posttest, was to provide the most stringent test for learning, in the sense that we did not want our participants' inability to remember details of formulas to hinder their performance.

During the collaboration session, each pair was asked to solve three physics problems. For the present paper, only 18 of the 30 problems were analyzed.[1] Nine groups solved the first problem, which contained 4 different concepts; 5 groups solved the second problem, which contained 3 different concepts; and 4 groups solved the third problem, which was composed of 2 different concepts. Henceforth, there were 59 concepts assessed across the three problems and ten groups.

Finally, a posttest measured the amount of material learned during the instructional phase (administered $M=5.0$; $SD=3.6$ days after the collaboration session). The posttest contained three problems, which were isomorphic to the pretest and collaborative problems (i.e., the same nine concepts were tested on the posttest).

Procedure

All of the participants were asked to study each of the first four chapters individually in the way that they found natural. Participants solved the problems on the mastery tests either while they read the text or after they were finished. When the participants were confident in their solutions, they submitted their answers to the experimenter, who then immediately scored their performance. If the student correctly answered 80% or more of the questions, then he or she was permitted to advance to the next chapter. If the criterion was not met, then the student was shown which problems were incorrect and encouraged to read the text and correct the mistakes. This cycle of reading and testing continued for the first four chapters until criterion performance was met. On average, students spent a total of 6.5 hours to reach mastery of the four chapters.

The pretest was administered after the students read chapter five. Once they were finished with the pretest, an instructional phase was scheduled. For the Collaborative condition, the pretest was not scored immediately, so that the participants were not paired on the basis of their pretest scores. Dyads were formed under the constraints that they finished the background material relatively close in time, and they were the same gender.

During collaboration, the dyads solved three force problems. They were encouraged to use their partners as a resource and to work together to understand and solve the problems. The entire text (chapters 1-5) was available to the dyads during the collaboration session. The Text-only group solved the same problems, but did so individually with the text available. After the instructional phase, the posttest was individually administered.

The sessions were recorded (both audio and video) and later transcribed. The transcription was based on the audiotapes of the dialogues, using information from the video for interpretations when necessary.

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[1] A subset was used because the performance data for the present study comes from a larger study in which all of the items were relevant.

Analyses and Results

Coding scheme

The first coding step was to segment the transcribed protocols. The segments were taken at the level of problem-solving episodes (i.e., several turns dedicated to a single concept). The boundaries of a problem-solving episode began with a proposed equation, and ended with either the final solution of the equation or the abandonment of a solution path altogether. Across all groups and problems, there were a total of 87 problem-solving episodes.

Episodes were then coded as other-directed explaining (ODE), self-directed explaining (SDE), or co-construction. Other-directed explaining occurred when a more-knowledgeable partner explained a concept to a less-knowledgeable partner. Pretest performance for each participant determined his or her knowledgeability status for each concept. Because each problem was composed of several concepts, the individual's status could change from one problem-solving episode to the next, depending on his or her pretest performance.

When the less-knowledgeable peer explained a concept during a problem-solving episode, either to a more-knowledgeable or equally knowledgeable partner, then the episode was coded as self-directed explaining. Again, pretest performance was used to determine knowledgeability.

Finally, when both partners were being generative in the conversation by adding significant and relevant contributions, the episode was coded as co-constructed. Co-constructed episodes were further decomposed into elaborative and critical co-construction, which will be defined shortly.

Once the problem-solving episodes were coded in terms of the conversational elements, the content (i.e., the physics concepts) was also coded. The content was then linked to the episode analysis, which allowed us to track the impact of dialog on posttest performance. For example, if a more-knowledgeable peer explains how to solve the compound body concept to her less-knowledgeable partner, then that episode was coded as "other-directed explaining *about* the compound body." To measure the learning effect of other-directed explaining on the listener, we then looked at her posttest performance on the compound body concept. Because some problems involved multiple solution attempts, only the final problem-solving episode was linked to the posttest concepts (N=59).

Collaborative problem solving resulted in learning gains

Did the individuals learn from the collaborative problem-solving session? To answer this question, we calculated gain scores for each individual, which controlled for pretest knowledge: $g = (post - pre)/(100\% - pre)$ (Crouch & Mazur, 2001). Thus, the gain scores reflect the increase (or decrease) in learning per concept, per person. Overall, there was an average net gain of 26% (while controlling for pretest knowledge), which was significantly different from zero (p=0.002).

Evidence that individuals learned from collaborative problem solving can also be found in the analysis of the control (Text-only) group. The gain from pre- to posttest for the Collaboration group was significantly greater than zero, while the gain for the Text-only group was not ($F(1,9)$=0.756, p=0.41) even through the two groups did not differ at pretest.[2] This suggests that the learning gains are due to the activities the dyads engaged in during collaborative problem solving, which is presented in the next three sections.

Other-directed explaining during collaborative problem solving

As stated in the Coding Scheme section, both the content and episode were coded together to give us a sense of the impact of other-directed explaining on learning. Table 1 contains an excerpt of one student explaining her reasoning to another. The example begins with Beth asking Abby[3] to elaborate on a previous line of reasoning. There are two features to note in this example. First, Abby's style is definitely instructional. Her intent is to explain, as clearly as she can, how to solve the problem (see Appendix problem 1.ii.). Second, Beth does not contribute much to the conversation, but merely indicates that she is attending to Abby's explanation with her use of continuers.

Table 1: Example of other-directed explaining

```
Beth: So like 14 newtons would be the net force
      acting on B?
Abby: No, this-the overall force is ten,

Beth: Mm-hmm.
Abby: but if you split it, if-if-both of the
      blocks, as we know, are accelerating at two
      meters per second.  If they're in contact
      then they have to be accelerating at the
      same, rate.
Beth: Mm-hmm.
Abby  And, because, by Newton's second law F-F
      [pause] equals mass times acceleration.  And
      we know the acceleration,
Beth: Mm-hmm.
Abby: of each block and we know the mass of each
      block.  So you can calculate the force-the
      force of each block.  Or the force acting on
      each block.
```

Of the 59 final problem-solving episodes, there were a total of 11 other-directed explaining episodes (11/59=19%). On posttest, the listener (i.e., the less-knowledgeable peer) correctly used 5 concepts that they had previously used incorrectly on pretest. The data are summarized in the left segment of Figure 1. The black bars represent the

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[2] The data for the Text-only and Collaboration comparisons is taken from the full pretest and posttest (see footnote 1).
[3] All names are pseudonyms.

percentage of the corpus dedicated to a particular dialog type, while the grey bars represent the gain scores of the listeners (controlling for pretest knowledge). While a gain of 5 concepts is encouraging, especially given that the text was unavailable during the posttest, the probability of learning from listening to other-directed explaining is low (5/11=45%). This is not entirely surprising, given the finding that receiving elaborated help does not always lead to learning gains (Webb, 1989).

It is also informative to measure the performance of the more-knowledgeable speaker. Figure 2 suggests that the speaker (ODE), who knew the concepts on pretest, maintained 82% of her knowledge by correctly demonstrating her knowledge of the concepts on the posttest (see white bars in Fig. 2).
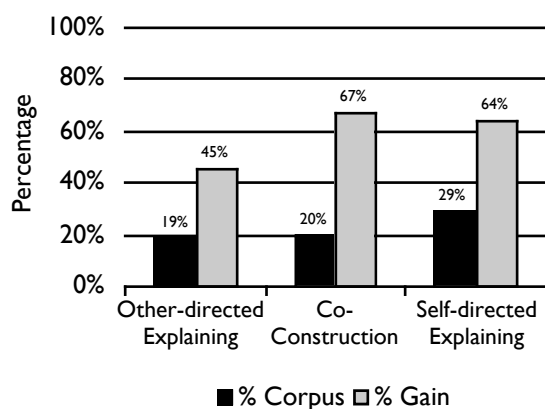

Figure 1: Gain scores associated with the absolute frequency for each dialog pattern.

Partners co-construct answers during collaboration

As stated in the introduction, co-construction is a hypothesized mechanism that has been proposed to account for learning from collaborative problem solving. A problem-solving episode was coded as co-construction when both partners were actively constructing new knowledge. The co-constructed solutions were further categorized as elaborative and critical co-construction. Elaborative co-construction was defined as one partner adding a significant contribution to the discourse that develops another person's idea. Here is an example of elaborative co-construction (Problem 2.ii.):

Table 3: Example of elaborative co-construction

```
Ron: It's the weight of the crate, which is ten,
     times    gravity    right?    [R    writes
     10kg(9.8m/s²)="] So it's, 98N, plus the five
     [R writes "98N+5"]-oh no, cause we don't know
     what it is yet, really.  Well I mean, it's-
Ben: Mg-Mg is the force exerted by the block, on
     the Earth.
Ron: Mg, that's,
Ben: Weight.
Ron: Mass times gravity, right?
Ben: Mm-hmm.
```

Episodes were coded as critical co-construction when they contained conflicts between the two partners (Druyan, 2001). The difference between partners' solutions led to a discussion where each attempted to convince the other how to solve the problem.

The following protocol excerpt is taken from Jill and Sara solving the compound body problem (see Appendix, Problem 1.i.). The question is difficult because it requires the solvers to represent the blocks as a single body; neither student demonstrated an understanding of this on the pretest. Sara believes the question implies that the acceleration should be found separately for each block, but Jill makes a case for the compound body. The conflict is between treating the blocks separately or jointly. Here is their argument:

Table 2: Example of critical co-construction

```
Sara: Yeah. It's just-it didn't say? I thought it
      said each of them.  [Reads: Find the
      acceleration of the blocks.]  To me that says
      find the acceleration of each block.  You
      know like, since they're two different
      kilograms.
Jill: It's going to be, the same though.
Jill: Because like, if we, go like this [pushes a
      book and pencil], and I do this, they're both
      moving at the same acceleration.
Sara: [Talks to Experimenter: 4 turns]
Sara: Because if you-well you can get a different
      acceleration by breaking it up though.
Jill: Oh wait. You know what? The acceleration will
      be the same for both of them.  Acceleration
      is the same for both of them. Force acting on
      block B, is different from force acting on
      block A.
Sara: Ok. Because their mass, is different.
Jill: Yeah. Because-yeah.
```

The frequency of co-constructive episodes is summarized in Figure 1 (see the middle bars). Two results are of particular interest. First, the amount of co-construction is similar to the frequency of the other-directed explaining episodes. More importantly, however, is the proportion of co-construction episodes that led to learning. Of the 12 episodes where the solution was jointly constructed, 8 of them led to the correct application on posttest (8/12=67%). Although co-construction was a relatively rare conversational pattern (12/59=20%), the reported frequency replicates prior estimates from a different domain (McGregor & Chi, 2002). Furthermore, the knowledge produced during collaboration was useful to both the individuals, which suggests the viability of group-to-individual transfer. That co-construction lead to a high proportion of learned concepts further supports the constructivist perspective that being active, as opposed to merely listening to a didactic explanation, is important for learning (Chi et al., 2001; Webb et al., 1995).

Co-construction was further decomposed into elaborative and critical co-constructive episodes. Of the 12 instances of co-construction, 5 were elaborative (5/12=42%) and 7 were

critical (7/12=58%). Elaborative led to a gain of 3 concepts (3/5=60%), whereas critical co-construction led to the correct application of 5 concepts on posttest (5/7=71%). Because of the small numbers, it is difficult to tell if elaborative or critical co-construction was more effective in subsequent learning. Follow-up research needs to be done to gain a better understanding of what drives learning from co-construction.

Learning occurs from self-directed explaining for speakers and listeners

Prior research has shown that good students spontaneously self-explain while learning from worked-out examples (Chi et al., 1989). Subsequent research has shown that prompting students to self-explain can lead to learning gains, above and beyond those who spontaneously self-explain (Chi et al., 1994).

Figure 1 suggests that self-directed explaining (SDE) also operates in a collaborative problem-solving context. The frequency of self-directed explaining is high relative to the other conversational patterns (i.e., other-directed explaining and co-construction). We observed 17 episodes of self-directed explaining, which accounts for 29% of the corpus. In terms of the average gain, self-directed explaining episodes lead to a 64% increase (see Fig. 1).

The effects of self-directed explaining can be further differentiated into the gain observed by the speaker and listener. In the present context, the listener is also trying to learn the material; therefore, she has a stake in the problem-solving process. Instead of being a passive recipient, the collaborative partner listens to and could potentially monitor the ensuing self-explanation.

As expected, the gain was proportionally high for the speaker (71%; see Fig. 2). While self-explaining is effective for the explainer, the question becomes, does listening to a self-explanation benefit the listener? The answer to this question seems to be mixed. To a certain extent, listening to another person self-explain can produce learning. Specifically, there was a net gain of 5 concepts for the listeners (5/17=29%; see Fig. 2). Therefore, it appears that observing reasoning in action (i.e., being the listener) is about as effective as listening to other-directed explaining (ODE). Further coding is needed to gain a better understanding of what the listener is doing while listening to a partner self-explain. One might hypothesize that the listeners benefit only when engaged in a constructive activity, which has received some empirical support (Webb et al., 1995).
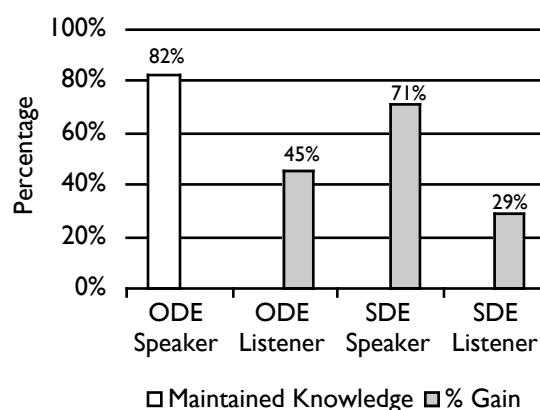

Figure 2: Gain scores as a function of dialog pattern and dominant speaker or listener.

Discussion

The primary goal of the present study was to demonstrate that several different mechanisms contribute to learning from collaborative problem solving. These three mechanisms were other-directed explaining, co-construction, and self-directed explaining. All of these mechanisms were associated with learning, but did so to different degrees. In terms of the overall proportion, self-directed explaining produced the strongest learning gains, with the caveat that the learning gains were greatest for the speakers. Other-directed explaining also lead to learning gains for the listener, but only to a limited extent. Several explanations given by the speaker during other-directed explaining did not translate into increased problem solving behaviors on posttest. Finally, co-construction, although relatively infrequent, led to increased problem-solving performance. Two-thirds of the co-constructed concepts were correctly used on the posttest.

A secondary goal of the present study was to demonstrate that multiple mechanisms operate within dyads. That is, one group may engage in other-directed explaining on a problem that one person understands (whereas the other does not). Then on the next problem, the same dyad may have to co-construct the solution because each individual has a different solution, and they must resolve their differences. Most research on collaborative problem solving measures the influence of one mechanism on learning in isolation of other potential explanations. The results from this study suggest that the pattern of communication is largely shaped by the background knowledge of the participants.

Finally, we attempted to show that self-explaining can take place in a collaborative context. While effective for the speaker, there was marginal utility for the listener. The effect was strongest when the speaker was engaging a partner with low pretest knowledge, but this effect needs to be substantiated by further research. The results from this study agree well with the idea that being constructive while solving problems leads to better learning and understanding.

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Appendix

Collaboration Problem	Concepts	Groups
1. Two blocks A and B are in contact with each other on a smooth floor. A force of 10N is applied to the blocks as shown in the figure. Masses of the blocks are 2 Kg and 3 Kg respectively. (i) Find acceleration of the blocks. (ii) Find net force acting on block B. (iii) Find force exerted by block B on block A.	N2Law CB N2Law N3Law	1,2 3,4 5,6 7,9 10
2. A person pushes a crate on a smooth floor. He is applying force at an angle q with the horizontal as in the figure. If the mass of the crate is 10 Kg, magnitude of the force is 5N and q=30 degrees, what will be the acceleration of the crate?	VD W T	5,6 8,9 10
3. Block A is attached to a string which is tied to a wall. The block is resting on a smooth plane inclined at an angle q with the horizontal as shown in the figure. Mass of the block is MA. What is the tension in the sting?	VD N2Law	1,2 4,7

Note. N2Law=Newton' second law; N3Law=Newton's third Law; CB=compound body; VD=vector decomposition; W=weight; T=tension.