Collaborative Explanations and Metacognition: Identifying Successful Learning Activities in the Acquisition of Cognitive Skills

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Abstract

Individual differences in collaborative explanations during learning were analyzed to determine effects on problem solving. Twenty-five university students with no prior programming experience worked through a sequence of programming lessons. For the Target lesson, subjects studied instructional texts and examples in either mixed performance-level dyads (collaborative dyad group) or individually (individual group) prior to individual programming activities. The collaborative dyad subjects were divided into equal sized groups of high-benefit and low-benefit dyad subjects based on Target lesson programming performance. Between-group analyses of the characteristics of the explanations generated by high-benefit and low-benefit dyad subjects were investigated, including (a) explanation and metacognitive strategies, (b) content of elaborations, and (c) manner of generating elaborations. High-benefit dyad subjects were found to generate both a higher quantity and higher quality of elaborations. These results are compared to findings from prior research on the self-explanation processes of solo learners.

Introduction

We commonly expect that working jointly with someone else in understanding some matter will yield better results than working by oneself. Often, this is because we feel that others will produce explanations beyond the bounds of our own thinking, and that we will also be compelled to construct and reflect upon explanations in ways that we otherwise would not have. However, it is not uncommon for such collaborations to fail. In this paper we present analyses of collaborative learning that are aimed at identifying the successful learning activities associated with explanation and metacognition. The present analyses were conducted in the context of a study that extends an established research paradigm in which computational cognitive models of knowledge acquisition have been developed as the basis for understanding the effects of individual self-explanation and metacognition.

The approach is motivated by our desire to formulate a scientific understanding of collaborative learning that coheres with established work on the learning mechanisms and processes of individuals. There have been few detailed examinations of collaborative discourse in learning (e.g. Miyake, 1986; Teasley & Roschelle, in press). Even fewer studies have analyzed the relationship between the actual discourse features contained in the collaborative interactions and subsequent student learning and achievement (e.g. Peterson & Swing, 1985; Webb, 1985). Consequently, interactional elements contributing to the success or non-success of collaborative efforts, or to the subsequent achievements of the individuals involved, remain little understood. On the other hand, a growing body of research on learners working alone with instructional materials has revealed the particular types of self-explanations that relate positively to high performance on subsequent problem-solving (Chi, Bassock, Lewis, Reimann, & Glaser, 1989; Ferguson-Hessler & deJong, 1990; Pirolli & Bielaczyc, 1989), and computational models have been proposed to account for these effects (Recker & Pirolli, in press; VanLehn, Jones, & Chi, 1992). We assume that this research on individual self-explanations will aid in our understanding the role of collaborative explanations in the development of conceptual understanding and problem-solving skills.

Explanations and Metacognition in Learning

Our interest is in the initial stages of cognitive skill acquisition -- determining how students learn from instruction so that they are able to apply what has been learned. The aim is to integrate models of active, goal-oriented learning processes with theories of problem-solving and cognitive skill development (e.g., Anderson, 1987; Brown, Bransford, Ferrara, & Campione, 1983). The educational context that we use in these studies involves learning from expository texts and examples followed by solving associated problem exercises. Learners are expected to vary in their study strategies and prior knowledge resulting in different interpretations and elaborations of the concepts, procedures, and examples contained in the instruction. Consequently, learners should differ in the quality of the declarative knowledge that they acquire from instruction, which in turn affects the acquisition of domain-specific cognitive skill. Effective study strategies should produce greater levels of higher quality declarative knowledge that can be used during problem-solving.

In earlier work in LISP programming (Pirolli & Bielaczyc, 1989; Pirolli & Recker, in press), learners working solo with instruction were ranked according to their subsequent problem-solving performance. Using protocol analysis methods extended from studies in physics (Chi et al, 1989) we identified particular self-explanation and self-regulation strategies that correlated with the better problem solvers. A more recent study (Bielaczyc, Pirolli, & Brown, in press) strengthened these correlational findings by showing experimentally that training students to use these strategies led to improvements in learning and problem-solving performance.

The present experiment extended this approach. More specifically, the current paper presents our analyses of the explanations produced by collaborative dyads working in essentially the same educational context and with the same instructional materials as our studies of solo learners. Learners were stratified according to the amount of benefit they seem to have gained from the collaborations and protocols were analyzed to identify correlated explanation and metacognitive activities. Although the experiment is also designed to permit comparisons of the explanation activities of dyads with those of solo learners, we leave that analysis to future presentations.

Experimental Design

The educational context for the experiment was a sequence of programming instruction using the CMU LISP Tutor (Reiser, Anderson, & Farrell, 1985). Twenty-five university students with no prior programming experience participated in the study (dyads, N=12; individuals, N=13). To control for gender effects all subjects were female. The study had three main phases: (1) three introductory programming lessons, (2) a Pre-Target lesson on helping functions, and (3) a Target lesson on recursion. The lessons typically lasted three hours and were scheduled 2-3 days apart.

All subjects worked through the introductory and Pre-Target lessons individually. Subjects were divided into groups of high-performers (PreH) and low-performers (PreL) based on Pre-Target lesson performance. Orthogonal to this grouping, subjects were divided into either a dyad group (PreH-PreL pairs) or an individual group. Prior to the Target lesson, the dyad partners practiced shared reading on a set of non-LISP activities. For the Target lesson, the dyad partners collaboratively studied the instructional materials then separated and worked individually on associated programming exercises. Measures of individual performance on the Target lesson problems were used to assess the effectiveness of the understandings acquired while studying collaboratively. As a control, the individual group performed the non-LISP and Target lesson activities on their own. Sessions were videotaped and "think aloud" protocols were collected for all activities.

Results

The programming performance of the dyad group was significantly superior to the individual group on the initially encountered recursion problems, although this superiority attenuated with practice. Further analyses of the individual-dyad differences will be presented in forthcoming papers. The focus of the present investigation is on the collaborative dyad subjects.

We were interested in determining the types of explanation activities related to successful learning. Our analysis method was similar to that used in the original self-explanations studies (Chi et al, 1989; Pirolli & Bielaczyc, 1989). First, subjects were divided into *high-benefit* (Hben) and *low-benefit* (Lben) groups using a post-hoc median split based on Target lesson performance. There were two dyads in which both partners showed high benefits from the collaborative interaction, two dyads in which only one of the partners showed high benefits (the PreH partner in one and the PreL partner in the other), and two dyads in which neither partner showed high-benefits. Next, the explanations generated by the high-benefit and low-benefit subjects while studying the Target lesson instruction were compared to determine if differences in explanation activities related to performance differences.

In order to examine the types of explanations generated, the explanation protocols of each dyad were transcribed and segmented into elaborations. We define "elaboration" as a pause-bounded utterance that is not a first reading of the instruction, nor conversation with the experimenter. Each elaboration was associated with the partner who generated it. Our coding scheme incorporated the same codes used in our prior self-explanation analyses: *Domain*: elaborations concerning computer programming, *Monitor*: elaborations about a subject's own state of understanding, *Strategy*: elaborations about a study method, *Activity*: elaborations about the materials or task, *Reread*: elaborations about rereading texts or examples, and *Incomplete*: utterances. In addition, a set of codes was developed to capture elaborations

Explanation Characteristics	High-Benefit	Low-Benefit	$t(10)$	p
Text Strategies: Identifying and Elaborating the Main Ideas				
Elaborating Main Ideas	28.5	13.2	1.90	.04
Coverage of the Main Ideas	12.7	7.2	2.80	.009
Example Strategies: Determining both the Form and Meaning of Example Code				
Concrete Evaluation	1.2	1.0	.76	.23
Recursive-Related	42.2	23.0	2.41	.02
Connection Strategies: Connecting the Text Concepts and Example Features				
Text-Example	15.0	6.5	1.87	.05
Example-Example	3.8	6.8	.69	.25
External-to-Lesson	2.8	.5	4.15	.001
Content of Student-Generated Explanations				
Structural Terminology	11.3	5.8	3.21	.009
Coding and Design Issues	4.2	.8	3.06	.01

Table 1. Explanation Characteristics of High-Benefit and Low-Benefit Subjects

more particular to collaborative discourse: *Domain-Help*: questions about a comprehension failure, *Domain-Check* requests for feedback for a domain elaboration, *Monitor-Other*: about monitoring partner's domain elaborations, *Monitor-Question*: monitoring partner's understanding, *Focus*: clarification statements, and *Acknowledge*: coordination statements.

The elaborations of each subject were analyzed for (a) explanation strategies, (b) metacognitive activities, (c) recursion-specific content, and (d) *skipped opportunities* for elaboration. The Domain elaborations were used to analyze (a), (c), and (d). The Domain-Help elaborations and several types of Monitoring elaborations were used to analyze (b). The statistical analyses below are based on logarithmic transformations of the data, however, the untransformed means are reported.

Explanation Strategies

We first examined the dyad protocols for a specific set of explanation strategies found to be related to high performance in our self-explanations research (Bielaczyc, Pirolli & Brown, in press). There were two reasons for this choice. The first was to determine whether similarities exist between the types of explanation and monitoring strategies used by individual learners and by collaborative learners. The second was to determine whether the use of these strategies in collaborative contexts similarly relates to high programming performance. Three particular types of strategies were investigated: (a) Text Strategies: identifying and elaborating the main ideas of text, (b) Example Strategies: determining both the form and meaning of example code, and (c) Connection Strategies: connecting the text concepts and example features.

Two analyses were performed in examining the use of the Text Strategies: comparisons of (a) the overall number of main idea elaborations generated, and (b) the distinct number of main ideas that were elaborated (Table 1). The analyses indicate that not only did high-benefit subjects generate more main idea elaborations overall than low-benefit subjects while studying the Target lesson texts, they were applying the strategy to a greater number of the main ideas introduced in the texts.

The analyses of the Example Strategies focused on two approaches to explaining example code: (a) evaluating the code using concrete values as inputs to the given LISP functions, and (b) elaborating the code with respect to the main lesson topic (Table 1). No difference was found between high-benefit and low-benefit subjects in the use of the first sub-strategy. To investigate the second sub-strategy, we examined the number of *recursion-related elaborations*, or elaborations focusing on recursive-aspects of the structure, operation, or design of the example LISP code. The high-benefit subjects were found to generate a higher quantity of recursion-related elaborations than low-benefit subjects while studying the example code.

In analyzing the Connection Strategies we examined several sub-strategies: (a) Text-Example strategies: clarifying the meanings of abstract

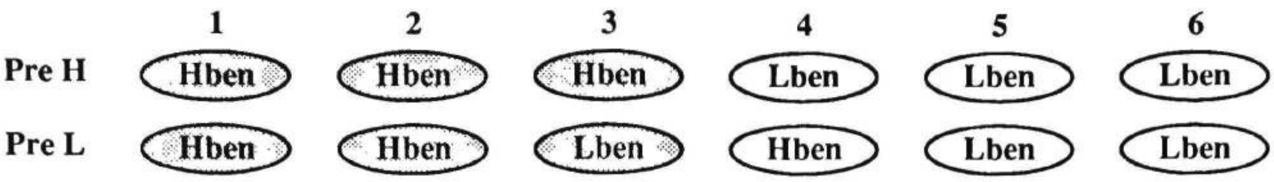

Figure 1. Frequent Usage of Domain-Help Strategy

concepts presented in the text by explicitly connecting the concepts to their instantiations in the examples, (b) Example-Example strategies: attaining a better understanding of how example code works by relating the code to other examples in the manual, and (c) External-to-Lesson strategies: integrating new and prior knowledge by relating lesson concepts to concepts external to those in the instructional manual (Table 1). Performance differences were found to be more closely related to strategy differences in connecting the text concepts to their example instantiations and connecting the Target lesson concepts to concepts external to the lesson, than to differences in establishing connections between the examples.

Summary Several of the same explanation strategies found previously to be related to high performance for individual learners were found to be similarly related for learners who study collaboratively. Although not all of the differences are statistically significant when the effects of multiple t-tests are taken into account, the general trend reflects that the high-benefit subjects apply the strategies more often than low-benefit subjects while learning from the Target lesson materials. The high-benefit subjects appear to be producing more elaborated representations of the Target lesson concepts and of meaningful relations underlying the LISP code in the examples.

Metacognitive Activities

We were also interested in the effects of metacognitive activities upon learning from instruction. We performed a set of comparative analyses based on several different types of monitoring elaborations (e.g. self-monitoring, monitoring by one's partner, total monitoring elaborations, comprehension failures). No reliable differences were found in the quantity of monitoring elaborations generated by high-benefit and low-benefit subjects for any of the categories.

Research in self-explanations has found positive relationships between performance and individual metacognitive activities, such as those indicated by the amount of monitoring elaborations (Bielaczyc, Pirolli, & Brown, in press; Chi et al, 1989). Thus, we were interested in whether other types of collaborative metacognitive activities related to performance differences. One particular activity is initiated by *Domain-Help* elaborations. The activity involves using one's partner as a question-answering resource during comprehension failures on domain concepts. Of interest are learners who both frequently ask for *Domain-Help* and receive a high number of responses providing relevant domain information. Subjects PreL-1, PreL-2 and PreL-3 requested help 2 to 3 times more frequently than any of the other subjects, and their partners all produced a high number of responses elaborating the domain concepts in question (shaded ovals in Figure 1). All members of these dyads were high-benefit subjects except subject PreL-3. Case studies of the three dyads revealed that, unlike subjects PreL-1 and PreL-2, (a) subject PreL-3 did not repeat or elaborate the responses she received from her partner, and (b) several of the responses provided by PreL-3's partner used concepts and analogies that PreL-3 was unfamiliar with.

Summary Although no differences were found between the number of monitoring elaborations generated by high-benefit and low-benefit subjects while studying, using one's partner as a question-asking resource during comprehension failure appears to provide benefits to both dyad partners. These results are consistent with the findings in the literature (e.g. Peterson & Swing, 1985; Webb, 1985). By asking direct questions and receiving an explanation, question-askers may be able to overcome points of confusion and comprehension failure and acquire information that may serve to fill in gaps in understanding. Conversely, by providing explanations, question-answerers may themselves acquire a deeper understanding of the materials. Close examination of the question-asking episodes suggests that a question-asker benefits most from a response when (a) the question-asker subsequently incorporates the received information into self-generated domain elaborations, and (b) the response is at the appropriate level for the question-asker.

The Content of Explanations

In addition to investigating strategic features or *how* the students elaborated the texts and examples, it is important to investigate *what* students say as they elaborate. The Target instructional manual introduces several central ideas about recursion. We examined subjects' elaborations for explanations of structural concepts (e.g. terminating case, recursive relation) and design concepts (e.g. the recursive case is *cdr* of the input list for list recursion) (Table 1). The high-benefit subjects generated elaborations covering a wider range of structural and design concepts than the low-benefit subjects. These elaborations may serve to build up a more integrated mental model of recursion. Such a well-connected model should provide a powerful knowledge base from which to draw during the subsequent task of programming.

Skipped Opportunities for Elaborating the Target Lesson Concepts

The focus of the final analysis is not on the elaborations that *were* generated by the dyad partners, but rather on those that *were not*. The Target lesson instruction consisted of brief texts and unelaborated examples. Due to the concise nature of the materials, it was assumed that students would need to generate additional elaborations for each text and example page in order to acquire an understanding of recursion that would enable them to write their own recursive LISP functions. Five of the six low-benefit subjects were found to skip generating any Domain elaborations while studying one or more pages of the instructional manual. Not elaborating the domain concepts on a given page is viewed as a *skipped opportunity* for attaining a deeper understanding of the concepts.

Discussion

Our fine-grained examination of collaborative explanations in the course of learning from expository texts and examples identified specific activities related to later success in the acquisition of programming skills. It appears that being a high-benefit subject -- a learner who was better able to solve Target lesson programming problems, was not pre-determined by performance on the Pre-Target lesson (i.e. before studying in a collaborative dyad). Rather, the results indicate that the high-benefit subjects were the learners who produced elaborated representations of the Target lesson concepts, built up an understanding of the relations underlying the examples, and made elaborations over a wider range of central concepts while studying the Target lesson instructional manual with their partner. Similar to our earlier studies of solo self-explanation (Pirolli & Bielaczyc, 1989; Pirolli & Recker, in press), the crucial factors related to improved learning seem to be both (a) generating your *own* explanations, and (b) generating explanations that allow the construction of an elaborated representation of the Target concepts. Although collaborative dialogues appear to provide additional metacognitive support and explanatory elaborations that might have been otherwise unavailable if the collaborators had worked solo, it is necessary for each individual to be actively engaged in processing the support and explanation in order for the dialogue to have a substantial learning effect.

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