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ABSTRACT

How the self-explanation process relates to learning and subsequent problem-solving performance was studied in two experiments with college students to examine whether students taught to self-explain during a study phase show greater test gains than control group counterparts; this is an attempt to replicate the results of M. T. H. Chi and others. The applicability of this approach to the domain of algebra problem solving was tested in two studies of algebra manipulation and algebra story-problem translation involving 32 college students. In addition, learning that occurs with worked-out examples was compared with learning that takes place when subjects generate solutions and receive feedback. Results indicate that self-explanation leads to greater test improvement (averaging 20% higher) for story-problem translation tasks in which conceptual reasoning is central, but it offers only a marginal advantage for the more procedural equation manipulation. It is a valuable learning aid, but advantages are restricted. One table and three figures present study findings. (Contains 20 references.) (SLD)

Learning Through Self-Explanation of Mathematics Examples: Effects of Cognitive Load

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Much of students' learning takes place as they read and study on their own, especially as students get older. Understanding the different study strategies used by high- and low-performance students may provide insight into student learning that is directly applicable to the development of instructional approaches. Recent studies demonstrate that good problem solvers tend to engage in more self-directed elaboration than poor problem solvers when they study worked-out examples and descriptive texts in physics (Chi et al., 1989), biology (Chi et al., in preparation), and computer programming (Bielaczyc & Pirolli in press; Pirolli & Bielaczyc, 1989; Pirolli & Recker, in press). The elaborations, or self-explanations, which appear to be most critical are those that signal inference-making, those that relate new knowledge to prior knowledge, and those that indicate that the student is monitoring his comprehension and trying to repair comprehension failures. Chi et al. (in preparation) showed that students prompted to elaborate on their understanding of biology texts exhibited greater test improvement than those not prompted even though the latter group's explanations were not suppressed. This suggests that the self-explanation process may be causally related to the observed increases in performance. It also suggests that this beneficial process may be teachable.

Objectives

The intention of this study is to advance our understanding of how the self-explanation process relates to learning and subsequent problem-solving performance. First, we examined whether subjects taught to self-explain during a study phase showed greater test gains than their control group counterparts, thus attempting to replicate the results of Chi et al. (in preparation). Second, we sought to extend the applicability of this potentially valuable instructional approach into the domain of algebra problem solving. Its use in studying algebra manipulation (Experiment 1) and algebra story problem translation (Experiment 2) were evaluated. Finally, we examined the effects that study format might have on the self-explanation

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process. Learning from worked-out examples was compared with the learning that takes place when subjects generate solutions and then receive feedback.

Theoretical Framework

In order to expand our understanding of the range within which self-explanation (SE) is a beneficial study strategy, we are examining its teachability, its applicability to a new domain (algebra), and its usefulness under different learning formats (examples or solution generation with feedback).

By examining the applicability of self-explanation to the domain of algebra, we may further evaluate the view that self-explanation is a domain-independent study strategy. The positive findings for physics problem solving suggest that it is indeed valuable for algebra. However, there are aspects of algebra which are predominantly procedural (Hiebert, 1986) and less articulable than the concepts of Newton's Laws and coordinate system selection which dominate introductory physics. The physics, programming, and biology learning of prior studies tap language-oriented (i.e., declarative) knowledge, and may be closer to the "story problems" found in algebra curricula. Thus we evaluate how helpful SE is for both algebra story problems and manipulation problems.

To date, self-explanation use has been observed while subjects studied texts and/or worked-out examples. Within Cognitive Load Theory (Sweller, 1988; Sweller et al., 1990; Sweller & Cooper, 1985), these media are considered to provide the learner with a "low cognitive load" because they help to focus the learner's cognitive resources, avoid splitting one's attention, and limit search activities which do not directly support learning. Problem solving, in contrast, is considered to be a high load activity since students must perform a large amount of search in order to locate appropriate operators, introduce appropriate constraints, and determine the path from the initial state of knowledge to the solution state. Sweller has shown that greater learning gains take place when subjects study examples than when they generate their own solutions. We predict that the process of generating a solution will interfere with the self-explanation process and thereby negate any benefits normally expected.

Method for Experiments 1 and 2

Subjects were either prompted or not to self-explain while they generated solutions from scratch (high cognitive load condition) or studied example solutions (low-load condition). In Experiment 1, SE and cognitive load are analyzed for their effects on subjects' algebra manipulation performance. In Experiment 2, improvement on algebra story problem-solving performance is assessed. The experimental method for Experiments 1 and 2 are presented together because of their similarity. Their only procedural difference is the dependent variable collected: manipulation (Experiment 1) or translation performance score

(Experiment 2). All subjects participated in both experiments in an alternating fashion (with experimental order found not to be significant). The results are presented separately for greater clarity.

Subjects (n=32) from the University of Pittsburgh psychology subject pool arrived individually for two one-hour sessions held one to two weeks apart. At the first session, a pretest was given and the training was administered. During training, subjects were instructed to either study a given worked-out solution (the low cognitive load task) to an algebra problem, or, if none was present, to generate their own solution (high load). All pretest and training problem solutions were presented to the subject after the final solution attempt and read aloud by the subject. For a given subject, high-load tasks were of one problem type (either manipulation or translation), while low-load tasks were of the other type (example stimuli are presented in Figure 1). Order was counter-balanced across subjects. In addition, half of the subjects were assigned to be self-explainers and briefly trained to provide an explanation after reading each line of an example solution or to explain each line of the solution which they generated. Non-explainers read each line of a problem and solution twice out-loud to equate their time-on-task with self-explainers (as per Chi et al, in press). Examples were removed after they were studied (as in Sweller & Cooper, 1985, but unlike Chi et al, 1989 where subjects had complete access to the examples). After a 1-2 week delay, a posttest was administered. In Experiment 1, each subject solved a set of algebra manipulation problems by solving for the unknown variable. In Experiment 2, each subject solved story problems by translating them into a set of solution-enabling algebraic equations.

Results and Conclusions

The effects of SE and cognitive load on manipulation and translation test performance improvement are presented here. Analyses are presented collapsed across both experimental order (manipulation first versus translation first) and the order with which high cognitive load was presented (first or second). Neither factor was not significant, nor did they participate in any significant interactions. It was also found that time on task did not differ significantly between subjects prompted to self-explain and those who read the materials twice.

Examples of students' self-explanations, along with the set of categories being used in the on-going protocol analysis is presented in Table 1. In this analysis, a self-explanation is defined as any utterance that adds some new information, regardless of its truth value. Analyses of the content of subjects' self-explanations will be reported elsewhere.

Manipulation. In a 2 (SE) by 2 (cognitive load) design with verbal SAT scores as a covariate (with 2 missing values) and manipulation gain scores (posttest minus pretest) as the dependent variable, the ANCOVA revealed no significant effects for SE, or cognitive load. There was, however, a marginal interaction with SE and cognitive load, $t(25)=1.7$, $MSe=.15$, $p=.1$, as is evident from Figure 2.

Performance improvement by non-SEs suffered under hi-load relative to lo-load, while improvement of SEs remained relatively unaffected by changes in the task format. The data also show Sweller and Cooper's (1985) general pattern of results; namely, that for non-SEs (all of their subjects), solution generation (high-load) impairs later performance. The lack of statistical significance between performance in the low- and high-load tasks for non-self-explainers (shown by the overlapping error bars) is likely due to the 1-2 week delay imposed between training and posttest (Sweller's posttest had no delay).

Translation. A 2 (SE) by 2 (cognitive load) ANCOVA (collapsing across order), with verbal SAT scores as the covariate (with 2 missing values) and story problem translation score as the dependent variable, yielded a main effect for SE, $F(1,25)=5.9$, $MSe=.6$, $p<.025$. Self-explainers improved significantly more than their silent counterparts (whose improvement was indistinguishable from zero), thus replicating the documented Self-Explanation Effect (Chi et al., 1989). There is also a main effect for cognitive load, $F(1,25)=6.76$, $MSe=.69$, $p<.02$. Subjects who studied examples outperformed those generating solutions (whose showed no improvement). As seen in Figure 3, a significant SE by cognitive load interaction was also found, $F(1,25)=7.1$, $MSe=.72$, $p<.02$. Improvement on the translation task for all treatments was negligible except for self-explainers who trained with a low cognitive load.

Conclusions. Self-explanation lead to large test improvements (on average, 20% higher) for the story problem translation tasks, where conceptual reasoning is central (Mayer, 1982), but offered only a marginal advantage for the more procedural equation manipulation (Lewis, 1981). SE is a valuable learning aid, but its advantages are restricted. Self-explainers studying story problem translation examples show an advantage in the low-load condition but they also show no performance improvement when a high cognitive load is imposed. This latter finding suggests that there may be a compeuition of cognitive resources. When generating solutions for story problems, the added burden of explaining one's actions may interfere with one's attention, memory storage or retrieval, or learning processes. As Sweller (1990) characterizes it, the generation of a solution involves a great deal of search and other resource-intensive processes that can interfere with learning (e.g., schema formation). The interference may also be modality specific. Verbal responses can interfere with verbal tasks (cf. Brooks, 1968) and tasks involving recognition and insight (Schooler et al., 1993). Non-self-explainers, however, show a consistent pattern of results for both manipulation (Figure 2) and translation (Figure 3), although this pattern is shifted along the vertical axis. The load effects were clearly most dramatic when the self-explanation strategy was employed.

SE appears to do little to enhance the procedural learning common to algebra manipulation. Its strength may be better suited to support conceptually oriented tasks such as modeling story problems. Additionally, subjects' explanatory structures may be likened to a network of interrelated situation models which are

fleshed out during elaboration (Recker & Pirolli, 1990). Without concrete instances of the mathematical principles (as provided by the examples), subjects have little to elaborate upon.

Significance For Education and Learning Theories

These results, pooled with those reported earlier, show a clear self-explanation advantage for a diverse set of school-based tasks, but focuses the scope of its effects. Self-explanation as a study strategy does indeed seem to be effective across a wide range of domains, but it does not appear to be universal. From these and earlier results, the claim is advanced that those studying conceptual material with the aid of worked-out solutions benefit most from the self-explanation process. The means by which the self-explanation process mediates conceptual learning is currently receiving a great deal of examination. One view is that self-explanations highlight knowledge gaps which cue learning opportunities (VanLehn & Jones, 1993). The implication here is that the primary learning takes place during the actual study/explanation phase. The interference effects due to solution generation that may be inhibiting the advantages normally found from self-explaining provide support from this view. In an alternative view, the primary learning occurs not at study time, but at a later time (during knowledge compilation) when the knowledge gained from studying example solutions is accessed and applied during a new problem-solving activity. Trafton & Reiser (1993) found that separating the target problem from the source problem hindered transfer. The rational is that, since memory for the source is inferior in this case, subjects must be drawing on the earlier episodes (making "ties", Bielaczyc & Pirolli, in press; Recker & Pirolli, in press) when transfer is successful. However, it is not clear that this is necessarily distinct from their contrasting model that posits rule induction (example generalization) during the study phase. Since rules need not only be learned in the rule induction view, but also properly applied during the transfer task, memory of the source may facilitate rule application. The findings of this current report may challenge the knowledge compilation view. Solvers operating under high load (solution generation) conditions may be expected to have a memory for the source problem comparable to that of the solvers studying worked out examples. Memory for the source problem in this set of experiments does not on the surface of it seem to be the primary factor in determining transfer performance. However, since this study was not designed to address this issue directly, and the interactions with cognitive load are not completely understood, this interpretation is necessarily tentative.

The finding that self-explanation strategies induced through experimental manipulation lead to enhanced performance has direct consequences for theories of learning and instruction. Since induced self-explanation enhances performance, it is likely that the self-explanation process somehow mediates the learning of good problem solvers, rather than simply being a side effect of good problem solving (evidence for this is also given by Bielaczyc & Pirolli, in press; Chi et al., in press). Since students can be

taught to apply these methods, learning deficits in many domains may be addressed by a very-accessible instructional intervention.

This research also begins to question what is exactly being manipulated across levels of cognitive load. Search may certainly be considered a process demanding of one's working memory resources. But students still engage in some search-based activities in their attempts to explain steps in a worked-out solution. As Catrombone (in press) shows, labels for steps in complex solutions helps to dramatically improve subjects later problem-solving transfer. Catrombone shows that it is the presence rather than semantics of the label that is most relevant to promote transfer. He speculates on how self-explanation processes may mediate subgoal formation, and how this in turn may be a major mechanism for fostering learning and remote transfer. Research such as the current report, Catrombone's work, and others may help to determine what belies the findings of Sweller's Cognitive Load Theory, and what its relation is to working memory load (Baddley, 1986), search-based processes, and transfer.

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Table 1: Protocol categories and example utterances

Categories	**Example Explanations From Protocols**
Monitoring	Comprehension Failure. *Oh, I don't understand how they got this on the other side...*
	Understanding. I know how to do that!
Inference / Elaboration	*At least we know they are both one hundred miles from each other...*
Impose a Goal	*Get W by itself.*
Interpret Mathematics	*When they have the same amount of money you can set both of them equal.*
Refer to Law of Mathematics	*And then you factor out an A.*
	You have to subtract it from both sides.
Meta-Strategy	*I'm not exactly sure how to set it up as an expressive problem, but I could do it long hand...*
Tie to prior learning	*Okay, it was the same back here*
Mathematical Activity	*The first day he would have ninety-seven [dollars], the second, ninety-four, the third ...*

	Problem	Worked-out Solution
Manipulation Task	Solve $a = d + ac$ for a.	1. $a - ac = d$ 2. $a(1 - c) = d$ 3. $a = d/(1-c)$
Translation Task	A cook makes twice as much as a waiter makes. Let w be the number of dollars per day a waiter makes. If the cook makes $95 per day, how much does the waiter make?	Waiter: w dollars per day Cook: $2w$ dollars per day $2w = 95$ $w = 95/2$

Figure 1. Sample stimuli with their accompanying worked-out example solutions (see text)..

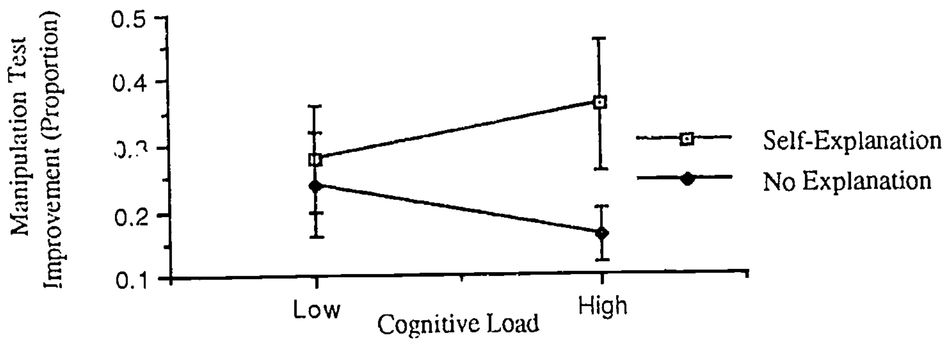

Figure 2. Test improvement on manipulation task for high and low cognitive load (Experiment 1).

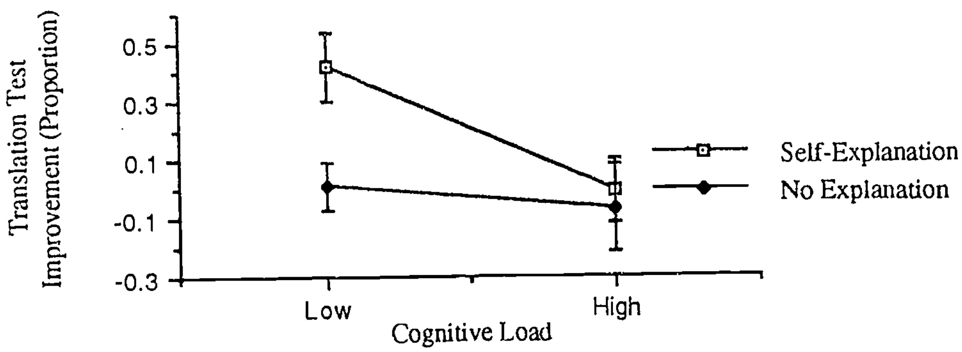

Figure 3. Test improvement on translation task for high and low cognitive load (Experiment 2).