Supporting Learning of Variable Control in a Computer-Based Biology Environment: Effects of Prompting College Students to Reflect on Their Own Thinking

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Abstract: While instruction on control of variables has been shown to be effective, especially when it encourages students to focus explicitly on rules or procedures, little evidence of application to novel problems has been obtained. We hypothesized that prompting students to understand their own learning processes while doing experiments involving control of variables would allow them to activate their repertoire of knowledge and strategies and learn in a way that would enhance transfer of learning. Students were assigned to one of four versions of a computer-based biology simulation learning environment, each employing a different type of prompt: reason justification, rule based, emotion focused, or none (control). Learning in this computer environment, college biology students designed and conducted experiments involving control of variables. Students' ability to solve both contextually similar (near transfer) and contextually dissimilar (far transfer) problems was assessed. The treatment groups performed equally well on contextually similar problems. However, on a contextually dissimilar problem, the reason justification group had significantly higher scores than the other groups. Qualitative data showed that the reason justification prompts directed students' attention to understanding when, why, and how to employ experiment design principles and strategies, and this in turn helped students to transfer their understanding to a novel problem. © 1999 John Wiley & Sons, Inc. J Res Sci Teach 36: 837–858, 1999

Control of variables refers to the ability of students to keep extraneous variables constant while investigating a factor or factors of interest (Lawson, Blake, & Nordland, 1975; Linn, Pulos, & Gans, 1981). Student understanding of the control of variables in experiments has long been viewed as playing an important role in science education. The *Benchmarks for science literacy* (American Association for the Advancement of Science, 1993) call for students by the end of the fifth grade to be able to recognize when comparisons might not be fair because some conditions are not kept the same. However, students of all ages have been shown to have difficulties in understanding and applying the concept to scientific inquiries involving problems of

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causal and correlational relationships (Ross, 1988; Sneider, Kurlich, Pulos, & Friedman, 1984). The *National Science Education Standards* (National Academy of Sciences, 1995) noted that "Students still have trouble with variables and controlled experiments" (p. 173). In this study, we explored whether providing students with metacognitive supports would enable them to develop deep understanding of control of variables and apply the knowledge to novel problems.

Factors that have been suggested to contribute to students' difficulty in understanding and applying control of variables include developmental-related requirements (Inhelder & Piaget, 1958; Kuhn & Angelev, 1976), complexity of task demands, degree of student self-directness, and the quality of instructional supports provided to students (Ross, 1988). For example, research has shown that students often do not learn to control variables without explicit instruction (Sneider et al., 1984), and application of control of variables is inconsistent and influenced by the content and context of the problems encountered (Lawson, 1985). Duggan, Johnson, and Gott (1996), in a review of data from the National Curriculum Council project in the United Kingdom, found that students' ability to identify variables declined with complexity of the task. In a study of seventh-grade students' science process skills in designing an experiment, Germann, Aram, and Burke (1996) found that less than half of students' experimental designs held nonmanipulated variables constant. Germann et al. (1996) hypothesized that students' performance of these science process skills was related to a variety of factors, including their comprehension of the task, familiarity with the context, previous experience, general understanding of science and science process skills, and communication abilities.

Other factors that have been shown to affect students' abilities to understand and apply control of variables include instructional factors such as: (a) a focus on memorizing procedures without explicit understanding about how and why to employ specific rules or procedures (Ross, 1988), (b) failure to help students notice salient features of sound designs versus bad designs in a given situation (Sneider et al., 1984), and (c) use of procedures divorced from any meaningful context (Schauble, Glaser, Duschl, Schulze, & John, 1994).

Theoretical Perspectives

A key factor in helping students learn to solve control of variable problems seems to be a focus on explicit understanding of procedures, design features, and the nature of context in which the problem is encountered. For example, in a meta-analysis of 65 studies which examined methods for teaching students how to control variables, the benefits of explicit instruction were amply demonstrated (Ross, 1988). A positive overall mean effect size (ES) on posttest scores (ES = 0.73) was obtained, indicating that overt instruction on the control of variables was generally successful. These positive effects were obtained across grade levels.

In his investigation of strategies to teach students control of variables, Ross (1988) distinguished among three categories of approaches: covert, implicit, and explicit. Covert treatments, which were the least effective (ES = 0.44), gave students opportunities to design controlled experiments but without explicit instruction. Implicit treatments, which were more effective than covert treatments (ES = 0.72), involved modeling by the instructor or instructor-led development of a procedure for conducting fair experimental tests. The most successful treatments (ES = 1.04) were those in which students were provided with explicit rules that described how to design well-controlled experiments or were given good examples of experiments to derive an appropriate procedure for controlling variables.

Most of the studies reviewed by Ross (1988) emphasized the importance of having teachers model or explain to students the relevant concepts, strategies, or procedures that can be used to solve variable control problems. In the present study, students were provided with prompts that required them to explain or justify their own problem-solving processes. This approach differs from most previous approaches in that students' understanding of variable control procedures and strategies was developed by having students explicitly justify and monitor their uses of these procedures and strategies. By supporting students to explicitly justify why, how, and when certain procedures, rules, or strategies were used, we hoped students would acquire deeper understanding of variable control problems. The key to our approach was to help students make their own thinking explicit and available for self-monitoring and revision.

Prompting students to justify and explain their thoughts is grounded in metacognitive theory put forward by researchers such as Brown, Bransford, Ferrara, and Campione (1983) and Flavell (1987), who maintained that becoming aware of oneself as a learner allows the student to reflect, monitor, and revise the process and products of his or her own learning. Helping students develop abilities to monitor and revise their own strategies and uses of resources may enable them to improve general learning expertise that can be used in a wide variety of settings (Brown, Campione, & Day, 1981; Scardamalia & Bereiter, 1985). In addition, by monitoring effectiveness of one's own learning and uses of resources, students may be able to see the need to pursue a new level of learning and understanding (Bransford & Nitsch, 1978; Chi, Bassok, Lewis, Reimann, & Glaser, 1989). The idea is to enable students to develop the ability to learn how to learn (Vye, Schwartz, Bransford, Barron, & Zech, 1997).

Prompting students to explain or justify has been shown to improve learning in subjects such as writing (Scardamalia & Bereiter, 1985), reading (Palincsar & Brown, 1984), mathematics problem solving (Shoenfeld, 1985), and lecture comprehension (King, 1994). The major goal for using prompts is to provide a means to externalize mental activities that are usually covert (Scardamalia & Bereiter, 1985). For example, in training students to write compositions, Scardamalia and Bereiter (1985) explicitly prompted students to explain goals, main ideas, relationships between ideas, and their own strengths and weaknesses. Students who received prompts demonstrated significant improvements in their writing compared to students who did not. Similar evidence was found in studies conducted by King (1994), who found that students provided with prompts excelled in comprehension and recall of information from lectures. Reciprocal teaching programs developed by Palincsar and Brown (1984) demonstrated that having students take turns prompting each other during reading facilitated comprehension.

While using prompts to engage students in metacognitive thinking has been shown to be successful in a number of domains, it has been little studied in science, especially as applied to problems involving controls of variables. In addition, researchers have noted that different types of prompts may lead to different learning effects (Rosenshine, Meister, & Chapman, 1996). Prompts that ask students to explain rules or facts that should be remembered are very different from those that ask students to justify their uses of concepts and strategies as well as monitor and evaluate learning processes. The latter types of prompts help students "conditionalize" their knowledge (Bransford, Sherwood, Vye, & Rieser, 1986) because they engage students in inquiries about what should be learned as well as why, how, and when effective strategies should be used. The most important advantage of these types of explicit prompts is that they focus students' attention on their own thoughts and on understanding the activities they are engaged in during the course of learning and problem solving (Brown, 1997). In addition, engaging students in such justification is likely to increase the probability that relevant information will be accessed when needed (Bransford et al., 1986).

In our study, we investigated the use of explicit prompts to engage students in metacognitive thinking and problem solving involving control of variables. We were also interested in the extent to which students would benefit from metacognitive supports when the learning goal was to develop a deep understanding of control of variables so that the knowledge could be employed to solve novel problems.

Purpose of Study

The major purpose of our study was to explore the effects of different types of instructional prompts in the context of a control of variables problem-solving activity. We were particularly interested in prompts that might lead students to make their own learning processes explicit so that they could develop judgments about whether their procedures and strategies were effective and appropriate. In our study, periodic prompts were provided to students to scaffold them in reflecting on their own learning processes during a computer simulation of a biology laboratory activity. Scaffolds are various types of instructional aids that are used to support learning in situations where students cannot proceed alone but can proceed when guidance is provided (Palincsar & Brown, 1984). The notion of scaffolds is directly related to Vygotsky's concept of a zone of proximal development—that is, the distance between one's actual developmental level and the level of potential development when learning is mediated by collaboration and guidance from more capable others (Vygotsky, 1978). Prompting is one type of scaffold that can be used to guide students' metacognitive thinking.

Three types of prompts were employed: reason justification (students were prompted to give reasons for their actions), rule based (students were prompted to explain rules or procedures), and emotion focused (students were prompted to reflect on their feelings); the control group received no prompts. These types of prompts were chosen because they were congruent with the major components of metacognition; according to Brown (1987) and Flavell (1987), metacognition is composed of one's own understanding of process, task nature, and emotional state. We hypothesized that only certain types of prompts would be effective in contributing to student understanding and improved performance on control of variables problems. We expected that when students were prompted to explain their own decisions and actions (reason justification), it was very likely that they would engage in self-assessment comparable to metacognitive processes involving planning, monitoring, evaluating, and revising. It was expected that the self-assessment would yield superior understanding and transfer of learning.

The study addressed the following questions:

1. Which specific prompts (reason-justification, rule-based, emotion-focused, or none) in a computer-based simulation of a biology laboratory activity were most effective in helping students develop a deep understanding of solving control of variables problems?
2. Were there any differences in the types of responses students generated due to the nature of prompts?
3. Were there any differences or similarities in the design strategies employed by the students from different treatment groups?
4. In general, how did students feel about the experience with the computer simulation and the prompts?

Research Design

To investigate our research questions, four versions of a computer-based simulation of a biology laboratory activity were developed. The computer simulation was designed to be open-ended and to provide students with opportunities to employ control of variables in a realistic problem-solving context. The four versions of the program represented four different treatment conditions. They differed only in the types of prompts (reason justification, rule based, emotion focused, or none) provided to the students.

In our study, the reason-justification prompts were expected to help students develop an understanding of their own strategies and procedures. Prompts of this type included: “What is your plan for solving the problem?” “How are you deciding what to do next?” and “How did you decide that you have enough data to make conclusions?” The rule-based prompts were used to help students understand the nature of the problem-solving tasks at hand. For example, students received prompts such as: “What variables are you testing?” “What conclusions can you draw from your experiments?” and “What were the experiments you did that led you to the solution?” Emotion-focused prompts were used to enhance students’ understanding of their own emotional state. Examples of this type of prompt were: “How are you feeling right now in dealing with this problem?” “How are you feeling right now?” and “How are you feeling right now compared to when you got started?” In the control group, students received no prompts.

The subjects, college elementary education students studying biology, were randomly assigned to one of the four versions of the program. Using the simulation program developed jointly by the instructor and the researchers, each student designed and conducted experiments on the behavior of simple organisms, isopods (pill bugs), in response to environmental factors. After conducting simulated experiments, the student would then attempt to draw conclusions about the organism’s behavior in response to various environment factors (e.g., temperature, moisture).

A pretest-posttest design was employed to assess students’ ability to apply control of variables to problem-solving activities. Two kinds of control of variables problem-solving tasks were used to test the depth of the students’ understanding. One required students to solve problems that were identical in the level of difficulty and complexity to the computer simulation problems with only surface-level differences. These contextually similar problems can be viewed as near transfer or within-task transfer problems (Detterman, 1993). The other kind of problem required students to solve an applied problem in a completely different context. This contextually dissimilar problem was very different from and more complex than the computer problems. Such contextually dissimilar problems can be viewed as far transfer tasks (Detterman, 1993). Analysis of variance was used to compare mean scores on the contextually similar and contextually dissimilar problem-solving tasks from the four groups. Qualitative data, including samples of students’ responses to prompts in the computer-based environment, students’ experimental designs while using the computer environment, and interviews, were also collected to verify treatment effects.

Subjects

Eighty-eight students enrolled in an introductory course in biology for elementary education majors at a major Midwestern university participated in this study as part of an extended laboratory activity. Most of the students were sophomores or juniors, and the great majority of the participants (95%) were female. All of the participants had the same instructor. All of the participants had prior knowledge of and experiences with control of variables through regular laboratory activities. They all had used computers as part of regular laboratory activities prior to the study, and so were comfortable with the technology. All of the participants passed an initial assessment on concepts and principles of control of variables administered before the experimental treatments.

Instructional Unit

Our research study was a part of a laboratory unit on effects of variation of environmental factors, introduced as a standard curriculum component of the course. The unit was adapted from Science Curriculum Improvement Study (1970) elementary science materials on the environment. In this unit, students learned that natural environmental factors do not remain constant. Temperature varies, humidity varies, light intensity varies, and these variations influence the behavior of organisms. For instance, within the environment of brine shrimp, salt concentration varies from one location in an estuary to another, and this affects the hatching of brine shrimp eggs. In the class lecture and laboratory sessions, students conducted scientific experiments to investigate various related problems. They were also engaged in activities that required them to learn how to interpret data sets to determine how environmental factors affect the behavior of simple organisms, isopods. Isopods are terrestrial crustaceans that are commonly found in dark, moist places such as under rotting logs. By observing their reactions to varying environmental factors in the laboratory, and interpreting the data in light of random behavior, human error, and control of variables, students could deduce isopods' natural habitat. The isopod activity was selected as the focus of this investigation because this problem has been historically difficult for students in the class, and students' lack of understanding of their own thinking and reasoning has been implicated by previous researchers as a factor inhibiting students from solving control of variables problems successfully (Lawson et al., 1975; Piaget, 1962; Scardamalia, 1977).

Design of Computer-Based Simulation Learning Environment

Within this curriculum context, we designed and developed a computer-based simulation program. In this computer program, students were first presented with a problem situation through an on-screen biologist named Paula. Paula had designed several experiments to test isopods' reactions to light or moisture and to identify which factors had the greatest impact on isopods' behavior. Paula's experiments were purposefully designed in a manner that violated principles about control of variables. As a result, Paula wrote in her lab report that her experiments were inconclusive, and she invited the students to help her fix her experiments and solve the problems.

To solve Paula's problems, students needed to be able to (a) identify the types of problems Paula had and why she could not draw any conclusions; (b) understand the general idea of control of variables; (c) decide which variables would have most potential to affect the results of the problem; (d) identify confounding variables that might obscure the results; (e) isolate variables as well as combine the variables appropriately; (f) identify experiments that did not produce useful data and repair them; (g) find appropriate ways to measure and explain the results; (h) understand random behavior to interpret experimental outcomes; and (i) replicate experiments to verify results.

Paula's problems were more complex than those solved by students during regular laboratory sessions. During the regular laboratory sessions, students were asked to do experiments that tested just one variable (e.g., how isopods reacted to temperature only). However, during the computer-based simulation activities, subjects were asked to conduct more complex experiments requiring the manipulation of two variables (e.g., how isopods reacted to both light and moisture).

A variety of resources were provided in the program. Features included a strategy advisor, dictionary, reviews of lecture sessions, help options, materials supply, and laboratory. Students could select materials from a simulated supply cabinet to design their experiments as needed (Figure 1). Once a student set up an experiment, the computer ran it and generated results that

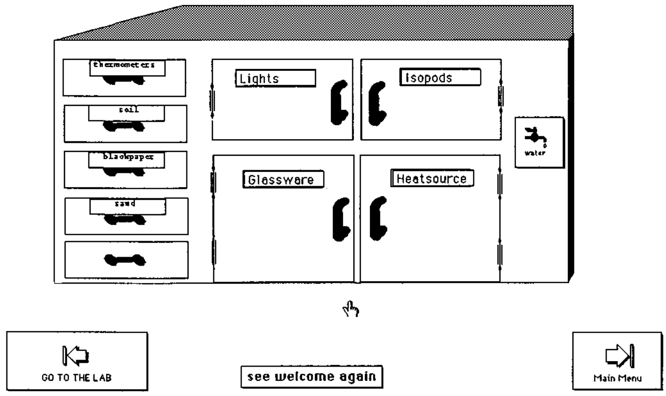


Figure 1. Simulated supply cabinet in the computer environment.

the student then attempted to interpret. No feedback was provided until after the student completed all of his or her experiments and attempted to draw overall conclusions.

All four versions of the program were identical in the types of structures, number of options, the resources available, amount of information, and locations of prompting. The prompts were embedded in three locations within the program, identical for all of the treatment groups: (a) after students had reviewed Paula's experiment, but before they had identified problems and selected any options; (b) after students had selected all of the materials and supplies for their own experiments, but before they had conducted experiments; and (c) after they had finished all of the experiments and drawn conclusions, but before feedback was given.

When the students were prompted, they had to enter their responses, which were saved by the program. Subjects could not proceed until they had given their explanations to the prompts. No feedback regarding the students' responses was given, since the prompt served the purpose of self-checking and making students' thinking explicit.

Several principles derived from the metacognition literature were used to guide the design of the computer program. Our first principle involved supporting students' learning of variable control in a specific problem-solving context, instead of treating control of variables as an isolated technique or procedure. Specific problem goals and situations helped students understand the meaning of the rules and procedures of control of variables in relationship to their immediate problem context. Studies conducted by Bransford and colleagues (e.g., Bransford & Nitsch, 1978) have shown that students' understanding of the usefulness of knowledge and skills is context dependent. Learning control of variables in a specific problem situation would thus help students understand how the rules and procedures were relevant and important.

A second principle was to provide students with opportunities to explain themselves instead of merely providing them with tools and resources to explore. A number of researchers have suggested that a discovery learning environment for science must do more than provide students with a world to explore (Schauble et al., 1991). In our program, in addition to providing students with resources, tools, and opportunities to make decisions by themselves, we provided students with prompts that scaffolded their inquiries by guiding their explanations and justifications. This gave them opportunities to make their thinking explicit and to identify their knowledge gaps.

Our third design principle was an emphasis on deep understanding as the learning goal rather than just finding the right solutions. For example, rather than instructing students to memorize explicit rules and procedures or how to perform experimental steps, our students were encouraged to conceptualize their actions. When the goal of learning is to understand and capture the significance of actions, students approach learning tasks very differently (Lin et al., 1995; Scardamalia & Bereiter, 1994).

Finally, in the program, students were encouraged to engage in self-assessment before feedback was provided. This gave students another opportunity to identify what they knew and did not know, which may have helped them be more ready for the subsequent feedback.

Procedures

The complete unit on variable control extended over 7 weeks of class. During the first 4 weeks, prior to the computer-based intervention, students attended the usual course lectures and laboratories. The typical course schedule consisted of 1 hour of lecture and 4 hours of laboratory per week. During this period, students were exposed to lectures and conducted laboratory investigations on organisms' responses to environmental factors.

Students were randomly assigned to one of the four treatment groups: reason-justification, rule-based, emotion-focused, or control. Prior to actual use of the computer-based simulation, students assigned to each group received instruction on how to respond to the specific types of prompts they would receive from the program during treatement. For example, the reason-justification subjects were coached to respond to the reason-justification prompts. They were not exposed to other types of prompts. Each group was also told about the purposes of using these prompts. The brief instruction was conducted because it has been suggested by Berry and Broadbent (1987) that concurrent self-explanation may only have a significant effect when accompanied by pretask instruction on how to respond to questions. They suggested that this type of pretask coaching may make the relevant information available in short-term memory at the time of explanation. Without preinstruction on how to respond to the prompts, especially those questions that ask subjects to provide information which requests recoding (e.g., "How did you come to this conclusion?"), self-explanation questions may force subjects to generate explanations from whatever information is available to them at that moment (Ericsson & Simon, 1980). Therefore, the intent of this coaching was to help subjects attend to the appropriate information at the time of responding to the prompts.

One month prior to the use of the computer program, students individually completed a paper and pencil problem-solving pretest. The students then participated in the use of computer-based simulation. The use of the simulation was integrated into the laboratory curriculum; no special credit or grades were awarded for participation in this activity. During the study, students attended a computer laboratory where they were seated at individual computer stations and worked by themselves on the computer simulation. Through the use of an assigned password, each student was presented with the version of the simulation program for the assigned treatment. Students' responses to the prompts in the computer program, as well as the time spent on the program, were recorded to a data file for later retrieval and analysis. In addition, students' notes generated during the computer experiments were also collected.

Following the treatment, subjects completed the posttest assessment of control of variables problem solving. In addition, 10 students, selected at random from each of the four treatment groups, were interviewed.

Data Collection and Analysis

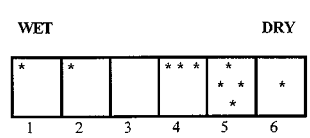
As previously noted, the ability of the students to understand and design controlled experiments was measured with two different types of control of variables problems: contextually similar (near transfer) and contextually dissimilar (far transfer). In the first type (contextually similar), students were assessed on their abilities to provide definitions, identify variables, and evaluate the results of an experiment involving the behavior of isopods. These items were very similar to the problems in the computer simulation. The second type of problem (contextually dissimilar) assessed students' abilities to design experiments involving control of variables to solve a contextually different and more complex problem. Figure 2 shows both problem types.

We chose these two levels of assessment for a couple of reasons. First, we would not be able to differentiate between deep and shallow levels of understanding if only contextually similar problem solving were assessed. We wanted to determine whether specific types of metacognitive support might lead to transfer of variable control understanding to applied tasks. Recent work has demonstrated that understanding at a surface level is neither sufficient nor necessary for far transfer tasks (Buerman & Greenfield, 1991). Therefore, a contextually dissimilar problem-solving task was warranted. Second, these two types of assessments were consistent with what Ross (1988) suggested to be important criteria for evaluating mastery of use of control of variables in the design of experiments.

The same tests were administered on both a pretest and posttest basis using paper and pencil assessments. A scoring rubric was developed based on students' abilities to: identify variables to be manipulated or controlled, explain experimental purpose, interpret experimental results, and propose an effective experimental design. A total of 20 points were possible on the contextually similar (near transfer) problem, while the contextually dissimilar (far transfer) problem was worth 6 points. Students' responses to the assessment items were analyzed and coded by two independent scorers and the instructor of the course. Interrater agreement among

Contextually Similar Problem

Suppose you had the following information for an isopod lab:
Ten isopods were placed in a trough in section 3, and after ten minutes, the following results were noted as diagrammed below:



Based on the diagram, answer the following questions:

a. What is the variable in this experiment and why?
b. How would you describe the response of these organisms to this variable (based on the diagram above)?
c. What is random behavior?
d. Do you see random behavior in the diagram above? Explain your answer.
e. What could you do to validate your results?

Contextually Dissimilar Problem

The elementary school in which you teach seems to have an unusually high number of hyperactive students. In fact, of the 100 students in second grade, 50 of them are hyperactive. Different groups of adults have proposed various ideas to explain this. The parents say that the **peer influence** causes them to be hyperactive. The principal thinks that the **family environment** is the cause of their hyperactivity. The teachers, on the other hand, say that **diet** is the source of the condition. You have been asked to design an experiment that would determine which one or more than one of these explanations is correct. (1) How would you solve the problem? (Please provide visual support to your solutions); and (2) Explain how and why you would set up the experiments to determine the cause or causes of the students' hyperactivity.

Figure 2. Contextually similar and contextually dissimilar problems.

the coders was 87%. Disagreements were resolved through discussion among the raters and joint reanalysis of the responses. Data collected from the assessments were analyzed using analysis of variance (ANOVA).

A manipulation check was performed for the purpose of confirming that subjects in the different treatment groups were in fact generating the types of responses to the prompts that were intended. The responses that were saved to disk from a random sample of 12 subjects from each of the groups were coded by two independent raters. Each statement made by a subject was classified into one of the three categories: (a) process or reason-based justification; (b) rule or concept explanation; and (c) emotional statement and others, according to criteria developed by one of the authors. Interrater agreement of 90% was achieved for the manipulation check.

The same 12 subjects from each of the four groups were also interviewed following the computer experiments. All of the interview questions were open-ended questions to elicit rich qualitative responses, and they were very similar across groups. Control subjects were asked all of the questions that the subjects from other treatment groups were asked except those questions about the specific prompts received during the problem solving. Interviews were tape recorded and transcribed for subsequent analysis. The interview data were analyzed using a cross-case analysis.

In addition, all of the subjects were asked to keep a record of their experimental designs while solving Paula's problem in the computer program. These data served two purposes: (a) a review for the students themselves, and (b) researchers' examination of students' design processes. Students' records of their computer experimental designs were represented by diagrams, which were classified into several categories and analyzed using a constant comparative method by the class instructor and the researchers.

Results

Quantitative Findings

Analysis of variance of the pretest scores on the control of variables problem solving showed no significant differences among the four conditions, contextually similar $F(3, 80) = 0.39$, $p = .76$, and contextually dissimilar $F(3, 80) = 0.27$, $p = .84$. Therefore, all four groups were about equal prior to the treatment; this was expected owing to randomization of subjects. Therefore, subsequent analysis focused on the posttest scores only.

Table 1 shows the results of the posttest assessment of contextually similar and dissimilar problem solving. Although the reason-justification group had the highest overall mean, differences among mean scores of the groups on the contextually similar portion of the control of variables problem-solving posttest were not statistically significant, $F(3, 84) = 1.90$, $p = .13$. However, the ANOVA for the contextually dissimilar portion of the posttest indicated a statistically significant main effect among groups, $F(3, 84) = 5.95$, $p < .001$. Student–Newman–Keuls (SNK) post hoc comparison of the group means showed that the reason-justification (metacognitive) group outperformed all of the other groups. The remaining groups were not significantly different from one another.

Overall time spent on the program, recorded in the computer data files, was also analyzed via ANOVA. The result showed that there were no statistically significant differences among the four groups, $F(3, 60) = .98$, $p = .406$. Subjects exposed to different treatments spent about equal time engaged in the computer-based problem solving. Therefore, time on task was not a factor.

Table 1
Results of contextually similar and contextually dissimilar problem solving posttest

Measure/Group	*n*	*M*	*SD*
Contextually similar problem			
Reason justification	21	18.09	1.50
Rule based	21	16.69	2.33
Emotion focused	22	16.59	2.33
Control	24	16.39	3.65
Contextually dissimilar problem			
Reason justification	21	3.47	1.12
Rule based	21	2.52	1.36
Emotion focused	22	2.31	1.72
Control	24	1.70	1.36

These comparisons indicated that all of the groups performed equally well on the tasks that required replay and recall of what they learned in the computer environment. The scores on the contextually similar (near transfer) problem task approached ceiling levels for all the groups. However, for the contextually dissimilar (far transfer) problem, which required students to solve a more complex and novel control of variables problem, the reason-justification group outperformed the rule-based and emotion-focused groups as well as the control group.

Research in transfer has shown that memorization or repeated practice may be sufficient for near transfer, because deep understanding is usually not necessary (Detterman, 1993; Salomon & Perkins, 1989). This may explain the fact that the treatment groups did not differ on the contextually similar problem-solving task. Far transfer, on the other hand, requires students to learn with a deep conceptual understanding of underlying structures and principles (Hatano & Inagaki, 1986). Only when students reach this level of understanding can knowledge and skills be adapted and used flexibly (Hatano & Inagaki, 1986). The superior performance of the reason-justification group on the contextually dissimilar problem-solving task suggests that prompting students to justify and explain their problem solving was more useful in helping students adapt their knowledge to solve a complex and novel problem.

Qualitative Findings

Given the above results, a question one would naturally ask is, "Why did the reason-justification prompts provide students with more benefits on the transfer task?" To explore this question, we did further analysis to see whether there were differences in the processes the subjects from different treatment groups engaged in during the work with the computer simulation. We were particularly interested in examining if there were any differences in (a) the types of responses generated by the subjects across different groups, and (b) the types of strategies evident in the experimental designs students generated during their work with the computer simulation.

Response Analysis. Different prompts were intended to elicit different responses. Were there in fact any qualitative differences in the types of responses generated? Students' responses (a sampling of 12/group) were segmented into propositions, the smallest meaningful units of statements (Chi, 1997). Each proposition was coded into one of the three categories by each of two raters. Table 2 shows the different types of students' responses and the different descriptive

Table 2
Response analysis categories

Type 1: Understanding of processes and procedures
- A. Planning (more than two steps ahead, e.g., "I will select a random sample of isopods, then separate the variables in this problem, which are light and moisture. I need to decide how to set up the trough to make sure that the size of the trough is identical.")
- B. Causal reasoning and hypothesis ("Will it make a difference in the results if I place a different amount of soil into the trough when I try to test moisture? Oh, I really have to make the amount of soil constant . . . ")
- C. Monitoring and evaluation (recognizing right/wrong choices and why, e.g., "Oh, I really don't need a thermometer because I am testing moisture right now": "I am not quite sure how testing interactions among light and moisture might work"; "I don't know how I got these results.")
- D. Revise ("I realize that I need to replicate what I have got in the first trial to draw more reliable conclusions.")

Type 2: Task-level responses
- A. Stating specific rules for the problem ("When I test light, I should keep the variable moisture constant"; "I need to decide how many experiments I should run.")
- B. Problem definition ("Paula's problem is that she tried to test two variables at the same time and then she could not explain her data patterns.")
- C. Recognizing the current state of the problem solving ("I got this answer right": "My second experiment yielded the right answer.")

Type 3: Emotional-level responses
- A. Positive ("I feel pretty confident"; "Now I calm down a lot.")
- B. Negative ("I feel frustrated"; "It was too confusing.")

categories collapsed under each. Interrater agreement was 90%; differences were resolved by mutual examination of the responses in question and development of agreed-upon judgments. After each of propositions was coded according to the scheme developed, we then calculated the percentages of statements in each category made by the students of different treatment groups.

It is clear that each group focused on the intended types of statements elicited by the targeted prompts (Table 3). For the reason-justification group, 79% of the responses fell into the understanding processes and procedures category that was consistent with the reason-giving prompts, 18% of the responses fell into the task level, and 3% were categorized as emotional. A typical process or procedure oriented response from a student was:

> I plan to set up the isopods in the trough with a light source, light bulb, at one end and the dark paper for the other end, and then I would switch the sides between the two because this procedure will allow me to make sure that the variable, position of the light, would not affect the behaviors of the isopods . . . rather, it is the degree of light that affected their behaviors. I want to learn how my designs would affect the control of other factors in the experiments. It is not a matter of simply controlling the moisture variable, while experimenting with light. It is much more complex than that, I think. . . .

For the rule-based condition, students generated responses that fell into the task category 78% of the time, and understanding of processes and procedures 16% of the time, and they made emotional related statements 6% of the time. A typical rule-oriented response from a student was:

> From our lab experience, we all know that we need to make plans, get hands-on experiences, test one variable at a time, replicate, evaluate results, and report the results. So, my

> plan was to set up 2 experiments to test the 2 variables separately instead of together like Paula did. I then got my materials together and ran the light experiment. I ran it 2 times to make sure the data I collected was accurate. I ran the moisture experiments 2 times for the same reason.

In the emotional-focused group, 64% of the responses related to feelings, 30% of the responses were made at task level, and 6% were related to understanding of processes and procedures. (Among emotional responses, 65% were rated as positive and 35% as negative.) An emotion-focused statement was: “The computer program started to treat me better now. I felt a little bit more confidence, except I couldn’t locate the foil. I wasn’t sure how to set up the light experiment. . . .”

Analysis of Students’ Design Patterns. While response analysis provided a snapshot of students’ cognitive processes, it did not reveal the nature of students’ problem-solving strategies. To examine how students in different treatment conditions differed in the strategies used to design their computer experiments, a constant comparison was performed to analyze the same 12 students’ design patterns and processes. The pattern analysis reported here was based on collected students’ notes and diagrams of their designs made throughout the experiment. Because of the flexible nature of the computer simulation environment, the sequence of designs was not the focus of our analysis. Instead of focusing on whether students tested light or moisture first, we were interested in whether the students approached their designs by using more systematic or random strategies (i.e., did they thoroughly test one variable before going on to test another variable, or did they use trial and error types of approaches?).

Three patterns of designs emerged after an initial analysis of students’ designs by two coders. The two coders evaluated the students’ designs separately. Interrater reliability was 89%, and differences were resolved through critical discussions and further analysis. These categories were used to analyze the strategies evident in the students’ on-line designs: (a) designs reflected successful attempts to control variables and showed a systematic approach involving thoroughly testing one variable before testing a second variable; (b) designs reflected successful attempts to control variables but were not systematic in testing one variable then another; and (c) designs failed to control variables adequately.

Students using Type A design approaches were more strategic or systematic about their design processes. They tended to develop a focus for a planned experiment, establish a framework for their designs, consider possible confounding variables (e.g., “Is the size of the trough the same for all?”), check back (e.g., “I can’t tell if the time for switching the light on would make differences here”), and only then move ahead. Type A designs showed evidence that the students em-

Table 3
Percentages of specific types of responses to program prompts, by group

	Reason Justification	Rule Based	Emotion Focused
Understanding of processes and procedures	79%	16%	6%
Task level	18%	78%	30%
Emotional	3%	6%	64%

ployed systematic strategies rather than guessing. Students would usually conduct new experiments only after checking, evaluating, and clarifying their previous designs. Actions were taken consistently rather than in a random manner. Students with Type A designs understood how differences in experimental designs affected the type of results obtained; they did not merely memorize the procedures or information given from the environment. Type A designs also seemed to help students gain new insights that they might not otherwise have been able to obtain (e.g., “It is not a matter of simply controlling the moisture variable while experimenting with light. There were other factors rather than major variables that I have to take into consideration. . . .”).

We found that students who exhibited Type A designs tended to ask themselves questions such as, “How can I make sense of my designs?” and “Why can’t I observe consistent patterns in my results? Is it because of the setups of my designs or because I did not interpret data appropriately?” In addition, we found that students who demonstrated Type A designs attempted to understand what conditions led them to choose particular designs and under what specific conditions failures occurred (e.g., “I added water consistently into the trough, by increasing 10 mL each time, because such a gradual increase would help me eliminate the confounding effects introduced by the amount of water . . .”). Most important, students developing Type A designs also showed greater flexibility by not repeating the mistakes made previously. The thinking processes we detected in students using Type A design strategies were consistent with the strategies defined by other researchers as strategic learning approaches, which are intended to help people make sensible decisions based on the understanding of their own learning processes in relationship to the materials and environments (Berardi-Coletta et al., 1995; Bielaczyc, Pirolli, & Brown, 1995).

Type B designs were designs that showed attempts to control variables, but where experiments were set up more randomly than Type A designs, and where it was usually more difficult to identify clear thinking and a logical approach to testing. In these designs, students often failed to follow through one experiment thoroughly. Instead, they tended to jump around testing different variables. They had difficulties in writing up reports to summarize their results. Students often started the design process all over again, rather than starting from where the problem(s) occurred.

Type C designs were of the type where students failed to show evidence of knowledge of how to “vary one thing at a time” or “equalize the effect of all other experimental variables.” For example, students who produced Type C designs would test light and moisture at the same time without holding a single variable constant, and they often conducted several random trials without separating the variables. Students did a lot of guessing in this type of design pattern.

We did not identify any designs that were systematic yet did not control variables. Most of the students seemed to be able to control variables, yet many were unable to be systematic and metacognitive about their design processes. Figure 3 shows an example of each type of design pattern as demonstrated by students’ experimental diagrams.

Table 4 summarizes the design results. The differences between the reason-justification group and the other groups in strategy use for design were striking. Most compelling was the fact that although most students could control one variable at a time, only a few students could do it in a more systematic manner by engaging in metacognitive types of thinking processes. Most of the subjects in our study knew rules of variable control in experimental design; however, they could not apply those rules to designs other than at a fairly basic level (e.g., testing moisture while controlling light).

Reactions to the Computer Experience. To determine how students felt about the computer learning experience and what suggestions they might have for future designs of the learning

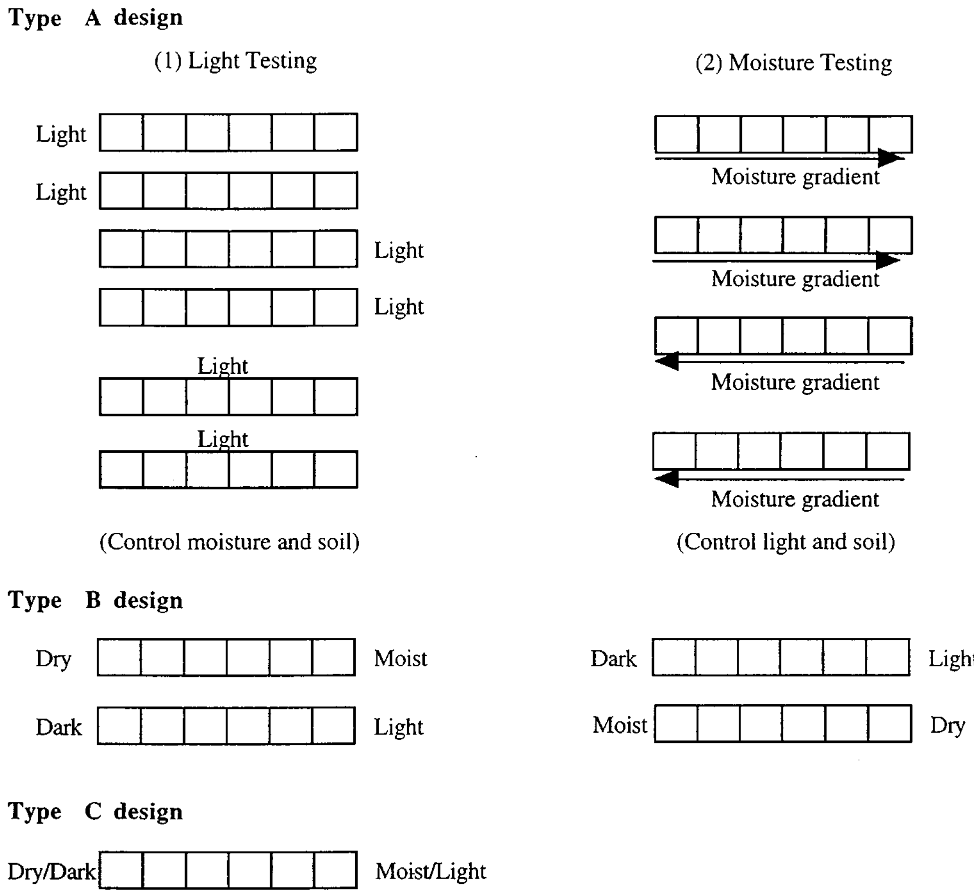


Figure 3. Examples of each category of student-generated experimental design.

environments to support variable control learning, we interviewed the same 10 students daily throughout the experiment, asking, “How did you like the program?” In this article, we report only the most interesting and relevant responses.

A majority of the subjects (59%) in the control group reported positive attitudes toward the program. However, 41% reported negative attitudes, often because they did not perceive the

Table 4
Categorization of student experimental designs, by group

Group	Type A Designs (Systematic Control of Variables)	Type B Designs (Nonsystematic Control of Variables)	Type C Designs (Inadequate Control of Variables)
Reason justification	9	2	1
Rule based	5	6	1
Emotion focused	4	6	2
Control	3	6	3

computer problem solving to be different from experiments they conducted as part of the regular laboratory activities. Some students also complained that the decision making was very difficult, and they felt nervous because no immediate feedback was given during the process. One control group student commented, “The whole computer experience made me nervous because I was not sure if I was doing right and I did not get any feedback from computers until the end. The decision-making part is also very hard.”

Responses from the emotion-focused group were mixed. Half of these subjects said that they liked the computer problem solving, and the program reinforced what they learned in lab. One student commented, “I really liked it. I think that it is much better than doing it in the real lab. It helped me better understand what I was doing in the real lab.” The other half of these subjects, however, did not have positive perceptions. One student remarked, “It was a little frustrating, and it required too much decision making.”

Sixty-three percent of the rule-focused subjects reported that they really liked the program, and 28% felt that doing experiments on computer helped them organize their thoughts to make more complete experiments. One student commented, “When I was doing it in the lab, it was kind of like nothing was together and I was separating everything in my mind. I think that my experiment with computer was more complete, organized.” Some subjects explicitly expressed appreciation of having control of the computer experiments. For example, one student noted, “It was neat how we could decide our own setup and how we were offered our own options and we could do whatever we wanted to come to our own conclusions about the whole experiment.”

Most of the reason-justification subjects (65%) said that the computer experience was good and interesting, and 35% of these subjects reported that the program made them think and enabled them to have more control over the experiments. One student from this group stated, “I feel that it enhanced our understanding of what we had done in the lab and lectures. And I think I learned more on the computer and it made me think more. It made me realize that I knew more than I thought I knew. . . . Doing experiments like this requires a lot more decision making.”

Overall, subjects across the four groups tended to view the computer experience positively. The frustrations and negative feelings that were expressed were related mostly to the challenge of decision making, lack of directions in using the program owing to its nonlinear nature, and the lack of immediate feedback concerning right or wrong answers. Subjects from the rule-oriented and reason-justification groups were the only ones who reported an appreciation of the degree of control they were provided while conducting the computer experiments.

General Discussion

In this study, we investigated the effects of different kinds of instructional supports on students’ variable control problem solving and transfer. Prompts were used as an instructional means to scaffold students in designing experiments in a computer-based simulation environment. We examined student learning of control of variables through on-line responses, design diagrams, daily interviews, and performance on a pretest and posttest of near and far transfer problem solving. The data were analyzed using both quantitative and qualitative methods.

On the posttest of contextually similar (near transfer) problem solving, differences among mean scores of the groups were not statistically significant. This result supports previous research in transfer which suggests that practice alone may be sufficient for near transfer, because deep understanding is usually not necessary (Detterman, 1993). On the other hand, the subjects in the reason justification condition performed significantly better on the contextually dissimilar (far transfer) problem-solving posttest than did the students in other groups. This indicates that prompting students to explicitly justify their own thoughts enhanced their ability to solve a far transfer problem involving control of variables. Why might this be so? Our fine-grained analysis of students' responses, design strategies, and reactions to the learning experience provided us some important insights into this question.

First, supporting students to explain reasons for their actions helped them organize their thoughts and resolve problems, which also helped them plan and monitor the design activities they engaged in. For example, a student who was prompted to make justifications commented,

> When I was responding to the prompts that asked me how would I plan my experiments, I stopped and thought for almost 5 minutes about what I should do. I thought about what were the goals for the experiments. . . . You know, when you are using computers, you always feel pressed to rush through to get the right solutions. Now I had to think about my plans and look at what I have done . . . where I was heading. . . . Going through these thoughts actually helped me become more efficient later on.

Second, justifying their actions helped students identify specifically what they did not understand and what they needed to know. For example, most of the students were aware of what they did not know in a general way. Students in the other groups often made statements such as, "I am confused" or "I don't know." However, the students in the reason justification group tended to be more specific about what they did not know. They would say things such as,

> I was able to do controlling variables by holding the light variable constant while testing moisture. However, I was unable to notice other potentially confounding variables . . . like the amount of water I poured into each trough and the amount of sand that I put under the trough. . . . But, how could I tell which variables may potentially confound moisture testing? I really needed instructions on how to decide which variables were potentially confounding variables. . . . I could not find any instructions within the computer program.

This level of monitoring and evaluation helped students identify specific conditions within which they failed to understand. In addition, such monitoring also set the stage for students to explore alternative designs.

Third, justifying their actions provided students with opportunities to make use of domain-specific knowledge to explain the procedures or steps taken. For example, students in the reason justification group generated explanations such as,

> After I decided to test moisture first, I did the following things: picked sand, selected water jars, beakers, and isopods. Then I poured 5 mL of water into Trough 1, 10 mL into Trough 2, 15 mL at 3 . . . water was added proportionally so that it would not affect the results. These things I did were all related to the concept of the variable control that we discussed in class.

To some extent, the ability to build connections between scientific principles and individual actions is congruent with the ability to learn about scientific "deep principles" (Brown et al., 1993). The deep principles help one organize thinking, see analogies, and develop abstract knowledge representations (Chi & VanLehn, 1991; Gick & Holoyoak, 1983). The abstract representations provide the bridge from one context to the other (Salomon & Perkins, 1989). In addition, by understanding the big ideas behind isolated procedures or steps, students may go beyond contextual differences to solve new problems more flexibly (Brown & Campione, 1994).

Lessons Learned and Future Directions

In this section, we share some lessons learned from our study and suggest directions for future research.

Other Ways to Make Thinking Explicit

One of the major goals for using prompts is to help students make their own thinking explicit so that thought processes can be used as objects for further evaluation and revisions. Although our study showed prompting to be one effective way to make thinking explicit, other approaches may also make students' thinking explicit and available for self-assessment. These should be explored. For example, a future study might explore the added value of providing social support to metacognitive thinking using technology. Learning environments such as Computer-Supported Intentional Learning Environment (Scardamalia & Bereiter, 1994) and other networked computer tools could be used to have students prompt each other to explain their thought processes while solving variable control problems. Learning in such environments, students could compare and contrast their own justifications with those made by others and revise problem-solving approaches. Video technologies also offer great potential to support students' metacognition. Research conducted by Bielaczyc et al. (1995) demonstrated the value of using video to model self-explanation processes while students learned Lisp programming. Similar approaches might be explored in learning to solve variable control problems.

Types of Prompts

This study showed that not all types of prompts are equally effective in supporting problem solving. When using prompting, educators need to be careful about what specific types or combinations of prompts are used. It is also possible that even the same prompts may generate different learning effects when they are used in different contexts and with different people and tasks. For example, in our recent pilot study, we observed that the prompts that were effective in this study with college students were not sufficient to engage a group of sixth-grade at-risk students in generating quality metacognitive explanations. Future studies should explore how the effects of specific types of prompts vary with the nature of student population, learning tasks, and classroom structures.

Timing of the Prompting

Another area of possible future investigation concerns when and where it is best to prompt. Although prompts focusing on rules and emotions did not enhance students' ability to solve the far transfer problems in this study, we do not know to what extent if any this may have been a function of the timing of prompting. In the present study, all of the students received prompts at the same time and in the same locations. It is possible that rule or emotional prompts provided at different times or in different phases of problem solving might have yielded different effects. For example, we used similar emotional prompts (e.g., "How are you feeling right now?") throughout the program. We found that students responded differently at different stages of problem solving. At the beginning, most students would respond, "I am really nervous and I do not know what I am supposed to do." In the middle, we found students saying, "I feel very stressed. I must have done something wrong in my design. . . . I need to examine how I set up the experiments and why I did it that way. . . ." At the end of the experience with the computer, most of the students said things such as, “I am feeling so good that I got it done. I can’t believe that I could do it!” These data tell us that timing and location may bring about differences in the effectiveness of the prompts. In the future, we should explore how the same type or different types of prompts are influenced by timing factors.

Role of Domain-Specific Knowledge

In our study, we encountered no instance in which students were unable to explain themselves at all. In part, this may be because our program was used at a later stage of the curriculum unit when the students had already gained a fair amount of domain specific knowledge from the lecture and laboratory sessions. However, it is not clear whether a well-articulated knowledge base is required for students to benefit from prompting approaches. Would the effects achieved with reason justification prompts be maintained in the absence of a domain-specific knowledge base? Can different types of prompts help one achieve an understanding of the domain knowledge initially, and how would such an understanding enhance access to the knowledge later on?

Role of Conversation and Feedback

The reason-justification prompts encouraged students to generate justifications for their actions or decisions. However, students were not provided with any feedback about the quality of their explanations as they would have if they were in a classroom conversation situation with teachers or peers. Would students benefit if guided conversational environments were provided to support learning variable control problems? In such an environment, students might receive feedback from peers, teachers, or other members of the learning community. The challenge in such an environment becomes how to provide appropriate feedback. This would be an interesting avenue of exploration.

Assessment and Transfer

Students provided with reason justification prompts outperformed students from other groups in far transfer problem solving. However, we cannot conclude that all other prompts are necessarily ineffective in all situations. For example, if our goal for learning were to have students remember a procedure for control of variables, the rule-oriented prompts might be most effective. If our goal were to have students develop an awareness of their own emotional state, the emotion-focused prompts might be most successful. Thus, we propose that the assessment of effectiveness of different types of instructional scaffolds depends on the learning goals.

In summary, more research is needed to fully understand how to help students make their own thinking explicit and available for self-reflection, and to make problem solving and other types of learning more meaningful in the classroom and in the minds of students. Our experiences in helping students make their thinking explicit led us to experience changes in our own thinking about learning issues related to control of variables problems. We hope that our speculations and reflections generate more conversations about designing learning environments to support students’ learning related to important topics in science education.

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