AC 2009-1746: SELF-EXPLANATION FOR EFFECTIVE LEARNING IN ENGINEERING CHEMISTRY: AN EXPLORATORY STUDY FOR INCOMING FRESHMEN

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Self-Explanation for Effective Learning in Engineering Chemistry: An Exploratory Study for Incoming Freshmen

Abstract

New students in engineering and science typically face difficulties in adapting their learning strategies to the requirements and challenges of college education. One of the major factors that challenges students engaged in this transition is their ability to build and successfully use deep-reasoning skills. To address this challenges instructors need to employ instructional strategies that shift students' focus from memorization of procedures and equations toward the integrative use of prior and new knowledge introduced in the classroom.

In this paper, self-explanation was proposed as the core element of such instructional strategies because it relies on the explanation a learner generates on his or her own as opposed to the explanations provided by an external source such as an instructor or a book. The primary goal of this study was to explore to what degree the use of self-explanation strategies improve students' performance on basic chemistry problems. Because self-explanation involves proper use of prior knowledge, a second goal of this study was to find if the level of prior knowledge influences the effectiveness of self-explanation. A number of 52 incoming freshmen students enrolled in the introductory chemistry module of a three-week summer learning program participated in the two-group between subjects completely randomized experiment used in this study.

The results of this exploratory study suggest that engaging students in a self-explanation behavior using guiding questions can be an effective tool in chemistry learning. However, the effectiveness of this strategy is diminished if students did not reach the threshold of domain-specific prior knowledge required by the complexity of the task. This strategy can be easily adapted to increase the effectiveness of tutoring sessions, review sessions, or short transfer story problems.

Introduction

With many students struggling with the concepts they learn, their instructors often ask themselves "How can we help them?" In science and engineering, this question often revolves around the thread of coherent reasoning built around questions or question-driven story problems that the instructors ask and the answers they receive from their students. Questioning is one of the most fundamental cognitive components that guide human reasoning [1]. Very often students engage in memory search and retrieval strategies in answering instructor's questions, strategies that are not sufficient for sense making. In order to comprehend materials, students need to relate new ideas to prior knowledge, reason from that knowledge, and synthesize that new knowledge into stronger mental models. They must learn to answer deep reasoning questions that articulate causal chains, actions, and logical justification [1].

In this study we look at a potential strategy to support students' deep and coherent reasoning by analyzing how instructors can use self-explanation [2] to support students' learning in chemistry. Research on self-explanation [2,3] shows that significant gains in performance on task can be achieved when people use this strategy [4].

Self-explanation and deep learning

The term self-explanation or self-generated explanation [2] refers to the explanation a learner generates on his or her own as opposed to the explanations provided by an external source such as an instructor or a book. Reported gains in science education attributed to the use of self-explanation are overwhelming, with self-explainers sometimes performing twice as well as the non-self-explainers [4]. Self-explanations are usually more effective than the explanations provided by others because (a) they require students to actively elaborate their prior knowledge, thus triggering more constructive processes, and (b) self-explanations are usually very well targeted toward the student's specific problem or issue.

The effect of self-explanation has been investigated on subjects in a variety of conditions and tasks on subjects ranging from middle school to college. Such research includes physics problem solving [5], computer programming [6] or emotion understanding [7]. As for how self-explanation takes place, scholars have studied so far situations when the explanation is spoken aloud or in one's head [8] and when it is written or typed [9]. They also documented the fact that self-explanation helps both when feedback on the correctness of the answer is provided [9] and when it is not [2,10].

Looking at the bottom line, self-explanation was studied in the context of gap-detection and gap-filling [2,11,12], mental model revision [13], conflict detection and resolution during knowledge integration [10], thought organization [11], and error detection and self-correction [4]. By construct, scholars have looked at schema formation and case-based reasoning [8], analogical enhancement [6], visual/verbal integration [9], construction of new knowledge [2,12,13,14], connection of principles to action [11], and situational model building [15].

Thinking of self-explanation as a domain independent strategy, Nathan et. al.[16] found that it works better for conceptual reasoning while providing only marginal advantage for procedural contexts. They also noted a decrease in performance when the cognitive load is significant, situation that suggests the existence of a competition for cognitive resources. Bielaczyc and colleagues [17] show that self-explanation is a strategy most high-performance students use, for example, when linking current concepts with prior knowledge. In his studies, the effectiveness of the strategy depends on the learners' domain-general and domain-specific knowledge, the comprehensiveness of the problem being studied, as well as the state of the students' evolving understanding. It has also been found that either guiding [17] or prompting [10] people to self-explain improves performance.

Self-explanation strategies in science education

Self-explanation is only one tool in the learner and instructor's toolbox. And, by no means can it be used alone as this and other research shows for example that prior knowledge of the domain where self-explanation strategies are applied can have a significant impact. It is though a domain-independent strategy that can be used across domains and age groups with the capability to support significant improvements in learners' performance. In this context, one important characteristic of self-explanation strategies we see is the ability to transfer and adapt successful strategies from one domain to another.

One area where self-explanation strategies can be successfully used is in tutoring. While some studies on self-explanation show that most learners do not spontaneously use self-explanation strategies [22] other studies suggest that learners seem to start self-explaining more when they are guided or prompted to do so [17]. Therefore one can consider that self-explanations strategies can be used to increase the effectiveness of tutoring or review sessions for problem solving through more intense conceptual engagement of the students. As an example, Chi [23] uses successfully strategies involving self-explanation in tutoring students to solve mechanics problems. In this case, the tutor's actions that prompted for the co-construction of knowledge (which includes self-explanation) proved to be the most beneficial in achieving deep learning, capable of overcoming misconceptions. That is, providing the tutees with support and opportunities to successfully construct answers on their own.

The use of self-explanation strategies proved to be beneficial in online environments as well. One of the attempts in using an online environment to scaffold the use of self-explanation was undertaken by Atkinson [24] and his colleagues who, in solving problems about probabilities, asked learners, aside from solving the problem, to specify the principle that applies to the particular problem they were working on. In this case a surprisingly simple procedure, prompt the participant to choose the principle underlying the problem, produced medium to strong effect on both near and far transfer.

These are only two examples of how self-explanation has been used successfully to improve learners' performance. As one can see, the interventions used in both cases are simple, nothing out of ordinary. What is important for success is the way they are used to support the learners' effective use of self-explanation strategies. Our research was developed to target same characteristics. We used prompt questions to elicit self-explanation at different stages in the learner's path toward the solution. The challenge was to find how to construct these questions and how to time them to produce the expected effect, self-explanation, and not give away the solution to the problem.

Context of the study

New students in engineering and science typically face difficulties in moving from learning strategies they effectively used in high school to ones that are effective for learning in a new context, college. One of the major factors that pose challenges to students engaged in this transition is their ability to build and successfully use deep-reasoning skills. From an institutional perspective, failure to address this challenge results in poor student retention that, in turn, results in decreasing, on long-term, the attractiveness of engineering and science programs. To expedite the transition from high school instruction to college level a three-week summer learning program was developed at a Midwestern engineering college to offer new students an exciting perspective on learning that will sharpen and enhance their academic skills. This program proved to be an excellent opportunity for incoming students to learn about coursework expectations, campus life, and community involvement. From an academic perspective, participating students take courses in Chemistry, Mathematics and English. This program gives the incoming students the opportunity to get an advanced start in the academic life while earning a 3-hour course credit toward their degree. The introductory chemistry module of this program was the focus of this study.

In this module, students engaged in a comprehensive study of general principles of chemistry with emphasis on chemical nomenclature, periodicity of the elements, chemical reactions and reaction stoichiometry, chemical bonding, and applications.

At the time of this study all students were exposed to the chemistry track during this summer's intensive preparation program that allowed them to address the task that they were presented with. As future engineering students it is also expected that they already had prior knowledge of chemistry when entering college. The summer program itself also simulated a "full semester" student life providing the students with the opportunity to take pop quizzes, do homework assignments, take formal exams, and get grades for their performance. A new dimension was added to the students' experiences by providing them with the opportunity to earn extra credit points for participating in this research.

Research questions

The primary goal of this study was to find to what degree the use of self-explanation strategies improve students' performance on basic chemistry problems. Because self-explanation involves proper use of prior knowledge, another goal of this study was to find if the level of prior knowledge influences the effectiveness of self-explanation. Therefore, for this exploratory study the research questions were:

Does the use of self-explanation elicitation questions increase students' performance on basic chemistry problems?

Does the self-reported familiarity with chemistry field, a proxy for students' perception of own knowledge of chemistry, impacts the effectiveness of self-explanation strategy previously mentioned?

Methods and Methodologies

Participants

Eighty incoming freshmen students enrolled in the previously mentioned summer intensive preparatory program were invited to participate in the experiment. They were asked to solve a short chemistry problem and to answer a few demographic questions. Participation was voluntary and rewarded with extra points for the chemistry section of their program. A number of 57 students answered this invitation of which only 52 students completed all tasks in the experiment. No outliers were found in the final dataset. Normality was a strong assumption for this dataset (one-sample Kolmogorov-Smirnov test indicated a $p > .05$ for all continuous variables used in the study).

Procedures and Measures

To deliver the experiment we used an in-house developed web-based application. The software randomly assigned students to one of two experimental conditions, control group or treatment group.

Both groups were presented with a question-driven problem typical for summative assessment in a basic chemistry module. The problem was based on the following scenario: *Adrenaline, also referred to as epinephrine, is a sympathomimetic monoamine that is produced by the adrenal gland. This stress hormone, when secreted into the bloodstream, rapidly prepares the body for action in emergency situations. It increases heart rate and stroke volume, dilates the pupils, and constricts arterioles in the skin and gastrointestinal tract while dilating arterioles in skeletal muscles. It elevates the blood sugar level by increasing catabolism of glycogen to glucose in the liver, and at the same time begins the breakdown of lipids in fat cells.*

Students in the control group were then presented with the main assessment question: *Given that adrenaline contains 3 oxygen moles, 13 hydrogen moles, 9 carbon moles, and 1 nitrogen mole, which is its chemical formula?*

In contrast, before being presented with the main assessment question, the students in the treatment group were asked to first answer following guiding questions: *(1) What type of chemical compound is adrenaline? (2) How does belonging to this type of chemical compounds influence the way chemical formulas are written?* and *(3) How do you write the formula for this type of compound?*

These guiding questions, developed together with the subject matter expert, aimed at engaging students in a self-explanation behavior. The nature of these questions emulated the causal structures an expert would activate when answering the main question.

Afterwards, the participants in both groups were asked to indicate how confident they are in the correctness of their own answer and to estimate their level of chemistry knowledge. In the end, the students were asked questions about their individual learning characteristics and to provide demographic information.

Dependent Variables

Two categories of measures were used for this study. The first category included measures of students' performance and the associated confidence that the answer they provided was correct. The performance was measured as a binary outcome 0 = wrong answer/1 = correct answer while the confidence in the accuracy of the answer was generated as a continuous variable, varying from 0 for low confidence to 100 for high confidence. To account for the complexity of students' performance an adjusted performance variable was computed as follows:

Adjusted performance = (-1)*Confidence for wrong answer and
Adjusted performance = Confidence for the correct answer

The resulted dependent variable, adjusted performance, ranges from (-100) for wrong answer and high confidence that the answer is right to (+100) for correct answer with high confidence that the answer is right.

The second group of measures tested if there is a significant difference between the control and treatment group in terms of individual characteristics associated with learning in this program and included motivation and academic efficacy, measures taken from Midgley et al.[18], constructs validated earlier by the same group [19].

These constructs used a five point Likert scale and the final value resulted as a mean of the items in each scale. The value of these variables varied from 1 for low to 5 for high value of the respective construct. Table 1 summarizes the statistical characteristics of these variables.

Independent variables

The first independent variable was the group to which the participants belonged, a categorical variable with two levels based on allocated experimental condition, control and respectively treatment.

Table 1

Means, Standard Deviations, and Pearson Correlations for continuous variables

	M	**SD**	**1**	**2**	**3**
1. Adjusted performance	11.22	73.75	-	.29*	.29*
2. Academic Efficacy	4.11	.58		-	.52**
3. Motivation Goal Orientation	3.93	.64			-

Note: *$p < .05$; **$p < .01$

The second independent variable, self-reported familiarity with the field of chemistry, was collected as a continuous variable varying from 0 for low familiarity to 100 for high familiarity with the field of chemistry. For the purpose of this study, we converted this variable into a two-level categorical variable by using a median split to define one *low* and one *high* category for the familiarity with the field of chemistry. This second independent variable was derived from the collected data to test if prior knowledge behaves as a moderator, as suggested by the existing research literature [17] where prior knowledge is viewed as an important ingredient for self-explanation effectiveness.

Design, Results and Interpretation

For this study, a two-group between subjects completely randomized experimental design was used. It is a between subjects design because a subject is member of only one of the two experiment groups, control or treatment. It is also a completely randomized designed because the participants were randomly assigned to one and only one of the two experimental groups [20].

The data associated with the individual differences between students in the control and treatment condition was analyzed using a one-way ANOVA with one between-groups factor, while the data associated with the performance on the task was analyzed using a factorial ANOVA with two between-groups factors, treatment condition group and respectively self-reported familiarity with the field of chemistry.

No statistically significant differences were found between students' learning characteristics in the two experimental groups as measured with both academic efficacy, $F(1,49) = 1.16$, $p = .29$, and motivation goal orientation, $F(1,49) = .63$, $p = .43$. Therefore, the two groups randomly created for this experiment have similar learning characteristics.

For the performance analysis the results were analyzed using a two-way ANOVA with two between-group factors. The omnibus ANOVA was significant, $F(3,48) = 7.26$, $p < .01$, and the between-subject analysis revealed a significant Group x Familiarity with Chemistry interaction, $F(1,48) = 11.29$, $p < .01$ (Table 2). The nature of this interaction is presented in Figure 2.

Subsequent analysis demonstrated that there was a simple effect for the condition group at the high level of familiarity with the field of chemistry, $F(1,24) = 18.08$, $p < .01$. As Figure 2 shows, the treatment group displayed significantly higher performance scores than the control group.

Table 2
Analysis of Variance for Adjusted Performance

Source	df	F	η^2	p
Between subjects				
Group (A)	1	11.94**	.20	.92
Familiarity with Chemistry (B)	1	2.01	.04	.29
A X B	1	11.29**	.19	.91
S within-group error	48	(3976)		

Note: Values enclosed in parentheses represent mean square errors. S = subjects. **$p < .01$

The simple effect for the condition group at the low level of familiarity with the chemistry field proved not to be significant, $F(1,24) = .01$, $p = .94$.
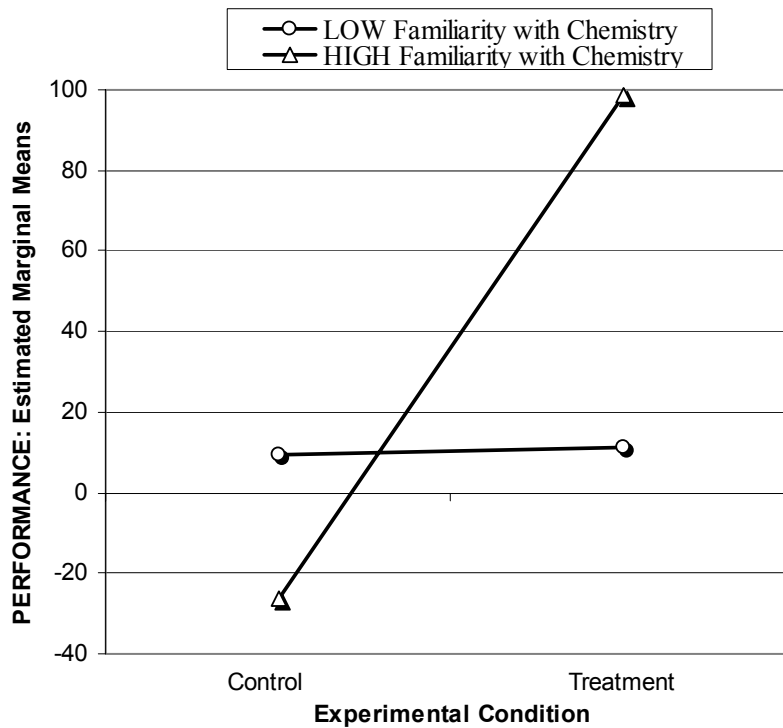

Figure 2. Performance as a function of the interaction between Experimental Condition and Familiarity with Chemistry

Because familiarity with chemistry can be interpreted as a proxy for perceived chemistry knowledge, this later finding suggests a strong moderating effect of perceived chemistry knowledge on the effectiveness of self-explanation, result supported by existing research on self-explanation [21].

Conclusions and future directions of research

The results of this exploratory study suggest that engaging students in a self-explanation behavior using guiding questions can be an effective tool in chemistry learning. However, the effectiveness of this strategy is diminished if students did not reach the threshold of domain-specific prior knowledge required by the complexity of the task.

On one hand, from a summative perspective this finding shows a limitation of the strategy to those situations in which prior knowledge is in place and readily available. On the other hand, from a developmental perspective these findings suggest that a layered deployment of self-explanation elicitation strategies can increase the effectiveness of knowledge construction. That is, early use of self-elicitation questions adjusted to the existing levels of prior knowledge followed by an increased complexity deployment of self-explanation elicitation questions can scaffold a more rapid construction of an increasingly complex pool of knowledge. Because this later developmental approach the nature of the questions used to elicit self-explanatory behavior is important, future research should look at how various characteristics of these elicitation questions, such as focus, atomicity, concept vs. process targeting, etc. influence learners' performance.

As existing research seems to agree upon the effectiveness of using self-explanation strategies in improving learners' performance, future research might focus on the relative effectiveness of different approaches used in scaffolding self-explanation in science education. For example, since the question asking strategy could impact the effectiveness with which self-explanation behavior is supported, future research could look, for example, at the effect of generic vs. specific prompt questions or at how timing of the prompt questions affects the strategy's effectiveness.

Another research direction could target the development and testing of a methodology for developing effective guiding questions for eliciting self-explanation behavior in large courses that use personal response systems (clickers), with the potential of increasing the effectiveness of this tool in stimulating active learning in large, heterogeneous courses. With the advent and expansion of online learning activities, further research should look for effective methodologies to scaffold self-explanation in online learning environments.

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