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Measuring Engineering Students' Metacognition with a Think-Aloud Protocol

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Measuring the Development of Metacognition in Engineering Students in a Problem-Based Learning Program with a Think-Aloud Protocol

This evidence-based practice paper focuses on how an engineering education program that promotes self-regulated learning impacts students' problem-solving skills. Iron Range Engineering (IRE) is an innovative, problem-based-learning (PBL) engineering program in Virginia, Minnesota. Throughout the curriculum of this program, students learn about and apply metacognitive skills necessary for self-regulating their learning. For the past several years, we have been conducting research funded by the National Science Foundation[1] to (1) identify the metacognitive skills inherent in self-regulated learning and provide evidence that students are acquiring these metacognitive skills during their *preparation* as engineers, and (2) understand if the preparation of students in this program (particularly in the area of self-regulated learning) gives them a "leg up" in their *transition* to the engineering workforce. To understand the effect of this unique undergraduate program on student preparedness for the engineering workforce, we have collected data from a variety of sources, including: think-aloud data collected during students' problem solving, student interview data, interview data from recent IRE graduates employed as engineers, and interview data of employers of the IRE graduates. This paper focuses on the first of our two research objectives. To this end, we are analyzing the think-aloud data as students solved an open-ended design problem to provide evidence that students are acquiring metacognitive skills necessary for self-regulated learning.

In this paper, we first give a brief background of metacognition and the use of think-aloud protocols to measure metacognition. Then, we describe our process of gathering think-aloud data from students, as well as our coding structure, which categorizes utterances as metacognitive or not, and, if metacognitive, whether the utterance is a type of *metacognitive monitoring* or *metacognitive control.* In addition, we detail our coding process and measures of inter-rater agreement. Finally, we share results to date, including comparisons of the think-aloud data from students about to graduate from the program with students entering the program.

Note that, at the time these data were collected, the IRE program was a two-year program, with students entering from various institutions at the beginning of their junior year. Throughout this paper, we will refer to these college juniors as "entering students" and we will refer to students at the end of the two-year program as "graduating students."

What is Metacognition? The capacity for life-long learning is critical for engineering practice and according to the Accreditation Board for Engineering and Technology (ABET, Inc.) is a required outcome for engineering accreditation (ABET, Inc., 2016)[2]. Metacognition, originally referred to as "knowledge and cognition about cognitive phenomena" (Flavell, 1979, p. 906), is a higher-order thinking skill and is key to developing life-long learning skills necessary for ABET and for an effective work career. Despite the critical role that metacognition plays in engineering education, surprisingly, it is rarely integrated into the curricula of engineering programs (Redish & Smith, 2008).

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[2] ABET, Inc., is in the process of changing some student outcomes required for accreditation. The new language proposed for the current "lifelong learning" criterion is: An ability to recognize the ongoing need to acquire new knowledge, to choose appropriate learning strategies, and to apply this knowledge

Metacognition is “knowledge of one’s knowledge, processes, and cognitive and affective states; and the ability to consciously and deliberately monitor and regulate one’s knowledge, processes, and cognitive and affective states” (Hacker, 1998, p. 3). This definition, and others (e.g., Brown & DeLoache, 1978; Kluwe, 1982; Schraw & Moshman, 1995; Veenman, Van Hout-Wolters, & Afflerbach, 2006), identifies both declarative and procedural components of metacognition (see Figure 1). Metacognitive declarative knowledge consists of a person’s knowledge or beliefs about: (a) one’s cognitive and affective states and the states of others; (b) a task, its demands, and how those demands can be met under varying conditions; and (c) strategies for accomplishing the task and how and when to use them (Flavell, 1979). Metacognitive procedural knowledge is derived through an individual’s monitoring and control of his or her cognitions (Nelson & Narens, 1990, 1992). Metacognitive monitoring refers to processes that are “directed at the acquisition of information about the person's thinking processes” (Kluwe, 1982, p. 212). These processes involve a person’s ability (a) to identify the task on which one is currently working, (b) to check on current progress of that work, (c) to evaluate that progress, and (d) to predict whether the expected outcome will be attained (Flavell, 1979). Metacognitive control refers to processes that are “directed at the regulation of the course of one’s own thinking” (Kluwe, 1982, p. 212). These processes involve a person’s ability (a) to allocate his or her cognitive resources to the current task, (b) to determine and direct the steps to complete the task, (c) to set the intensity or (d) the speed of the work task (Flavell, 1979).

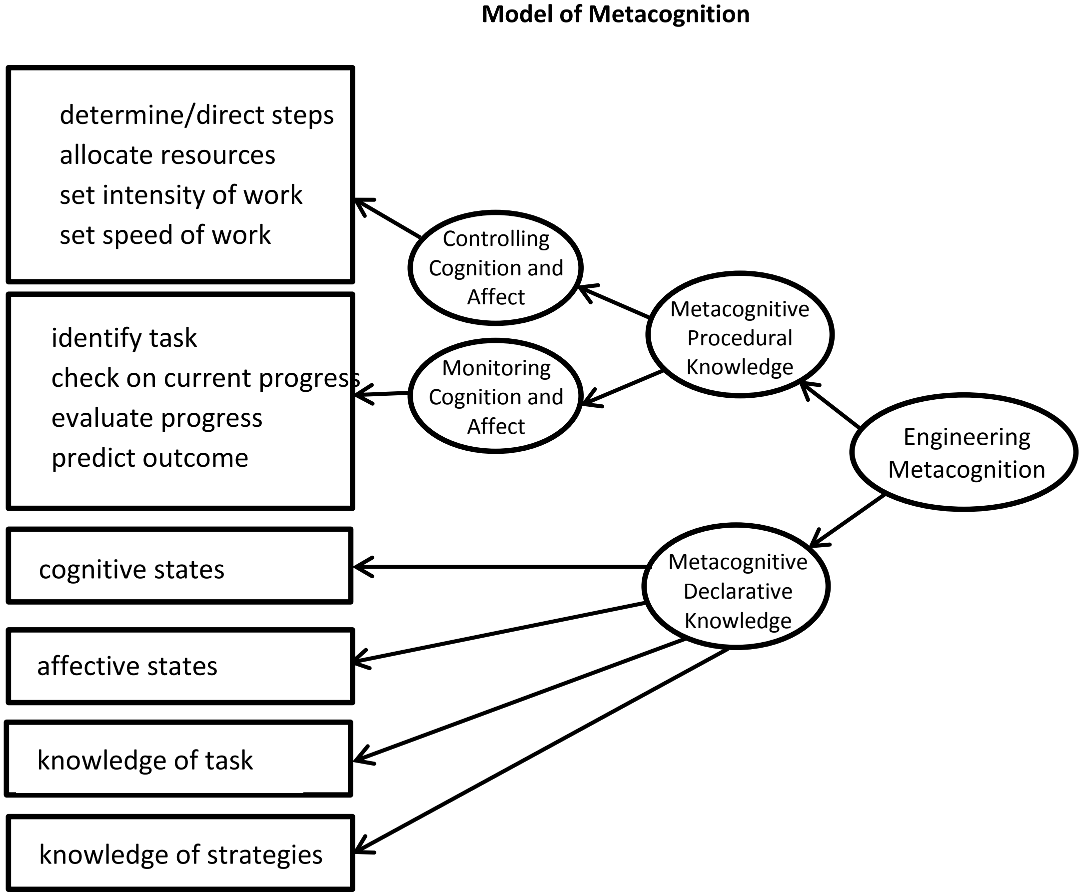

Figure 1. Categorization scheme for coding verbal utterances based upon Model of Metacognition.

Both declarative and procedural components of metacognition are necessary for students to become "self-regulatory organisms who are capable of assessing themselves and others and directing their behavior toward specified goals" (Hacker, 1998, p. 10), that is, to become agents of their own thinking. Metacognitive processes and strategies (Schroeder, Scott, Tolson, Huang, & Lee, 2007) along with motivational resources are necessary components for successful self-regulation of learning (Zimmerman, 2008). These skills are critical for development of workplace and lifelong learning, the major goal of formal education in general (Bandura, 1993, Zimmerman, 2008), but specifically required by the Accreditation Board for Engineering and Technology (ABET, Inc., 2016).

Although metacognitive strategies are linked to effective learning as well as life-long learning, few researchers have studied the development of metacognition in engineering students. The most pertinent studies concern the role metacognition plays in engineering problem solving and design in a school setting. One study used verbal protocols to compare strong and weak problem solvers in engineering statics and found "substantial differences in the use of self-explanation" between the two groups (Litzinger et al., 2010, p. 337). In another study, a small sample of students solving engineering statics problems showed an improved understanding of the problems (measured by verbal and written protocols) after an intervention featuring metacognitive instruction (Steif, Lobue, & Kara, 2010). And, metacognitive instruction has shown student gains in problem solving and design skills in several other studies (Hanson & Brophy, 2009; Koretsky & Kelly, 2011; Krause, Kelly, & Baker, 2012; Newell, 2004; Pappas, 2009; Zheng, Shih, & Mo, 2009; Zheng & Yin, 2012).

How is Metacognition Measured? Measures of metacognition typically have fallen into two general categories: Off-line measures are recorded either before or after learning, and on-line or real-times measures are recorded during learning. Researchers have debated which measures provide the best information about how well people can metacognitively monitor and control their learning (Schellings, van Hout-Wolters, Veenman, & Meijer, 2013). The debate likely arises because measures of off-line metacognition, which are derived primarily through the use of questionnaires, and measures of on-line metacognition, which are derived primarily through the use think-aloud protocols, have little association with one another. Correlations between the two types of measure typically range from -.07 to .31 (Veenman, 2005). Several explanations have been proposed for these low correlations:

- Verbal reports obtained during task performance may lack reliability and would not validly reflect people's cognitive or affective states;
- responses to questionnaires typically reflect people's beliefs or perceptions about their general learning and do not capture specific learning tasks; or
- questionnaires and think-aloud protocols measure different kinds of metacognition.

The first of these explanations has been addressed by several researchers, most notably, Ericsson and Simon (1994), Pressley and Afflerbach (1995), and Veenman (2005), who showed that verbalizations of one's concurrent thinking recorded during problem solving do not change cognitions occurring and are valid indicators of a person's cognitive activities. The second explanation was addressed by Veenman (2005) who showed that scores on questionnaires have little correspondence to behaviors or thoughts that occur during actual task performance. In addition, questionnaire data compared to data generated from a think-aloud protocol are believed to be more prone to distortion by reconstructions of memory, abstractions, interpretations, expectations, or errors from recollection (Breuker, Elshout, Van Someren, & Wielings, 1986). Finally, because of the low correlation between off-line and on-line measures, and because conceptualizations of metacognition consist of both declarative and procedural knowledge components, we believe that the last explanation has the strongest theoretical and empirical backing. Questionnaires measure off-line declarative knowledge of oneself as a problem solver, and think-aloud protocols more likely measure on-line procedural knowledge, including both monitoring and control processes. If researchers intend to examine learning when it is occurring, on-line, think-aloud measures appear to be more predictive of learning than off-line measures even when the off-line measures are obtained retrospectively (Veenman et al., 2006).

In our project, we are using both interviews and think-aloud protocols, and we expect to obtain two relatively independent sources of information on metacognition that will provide us a more complete understanding of the role of metacognition in engineering education. However, in the current paper we focus exclusively on engineering students' think-aloud data collected during their solving of an open-ended design problem.

Because of the rich data they provide, think-aloud protocols have been used since the early 20th century in psychological research and have been used extensively in writing research (Hayes & Flower, 1980) and other problem-solving activities. In engineering problem solving, researchers have used think-aloud protocols to study the engineering design process (Atman & Bursic, 1998; Atman et al, 2007; Ball, Ormerod, & Morley, 2004; Cardella, Atman, Turns, & Adams, 2008; Christensen & Schunn, 2007; Dixon, 2010; Dorst & Cross, 2001) and conceptual and problem-solving knowledge (Taraban, DeFinis, Brown, & Anderson, 2013).

A think-aloud protocol is a data collection procedure that involves the verbalization of real-time thinking while a person is solving a problem or is involved in other cognitive activity. The verbalizations are recorded, transcribed, segmented into units that can be coded via a pre-determined coding scheme that is based on *a priori* theoretical assumptions about the kinds of processes involved in a given task. The coded verbalizations are then used as measures of metacognition.

Although many researchers believe that the think-aloud protocol is a suitable data collection method, there are some shortcomings that need to be considered. For instance, think-aloud protocols cannot provide information about highly automatized cognitive or metacognitive processes. Some information concerning cognitive activities may be lost when learners fall silent. Not all thoughts can be verbalized without considerable interpretation (e.g., highly tactile tasks). Analyzing think-aloud protocols can be time consuming, which usually restricts their use to only a few participants in a study. Last, think-aloud protocols must be interpreted by trained raters who use well-developed coding schemes. Veenman and Alexander (2011) stress that the quality of interpreting think-aloud protocols depends critically on the adequacy of the coding system and that optimally informative research findings require optimally developed procedures for coding the verbal data. In the current research, we were mindful of these shortcomings and took measures to ameliorate those that were within our control. For instance, we used a short verbal prompt when students fell silent for 5 seconds, and before coding any data, we had developed a coding scheme that was based on *a priori* theoretical assumptions about the kinds of processes involved in a given task.

Method

Participants and Procedure. We have been in the process of collecting think-aloud data from two cohorts of IRE students. For each cohort we collect data at the beginning and at the end of their program. Because the IRE program is a two-year program for the third and fourth years of an engineering degree, we collect data at the beginning of the junior year and at the end of the senior year. Prior to the first cohort, we also collected pilot think-aloud data from a sample of graduating students in March 2015. The data discussed in this paper are from the 2015 pilot (graduating students) and the 1st cohort from January, 2016 (entering students); thus, the two groups represented in this paper are not pre- and post- groups, which means that there might be other differences between the groups that account for differences in the data.

The objectives of the think-aloud protocols are: (a) to measure the on-line thinking processes that are actively present as a person is engaged in problem solving an engineering design task, (b) to identify specific components of metacognition that are in play during problem solving, (c) to compare the relative presence of each component of metacognition during problem solving, (d) to differentiate the use of metacognition between novice and more expert students, (e) to measure the use of metacognitive processes and the association they have with the quality of problem solving, and (f) to substantiate the importance of metacognitive thinking during problem solving and contribute to the development of a model of engineering metacognition.

The pilot data included here were collected during a visit to IRE in March of 2015, when four graduating engineering students, all male, were asked to participate in a think-aloud, problem-solving task. The task was a design problem that asked students to redesign a motorcycle for use as a taxi in a mountainous and tropical island terrain. The design problem was adapted from Dixon (2010; see Appendix A). In Dixon's research, it is reported that the design task was vetted by two engineering professors with a combined 30 years of experience to ensure that it was sufficiently ill-structured and at an appropriate level of difficulty for students. After some recommended revisions, the task was vetted by one other professor who teaches a senior design project course who judged that the problem was suitable. The design problem was meant to as closely as possible represent open-ended problems that beginning engineers might be asked to solve on the job; however, true work problems are likely to be more complex. Immediately before the problem-solving task, students were asked to solve a warm-up problem, the purpose of which was to introduce the participant to the process of "thinking aloud." Students were encouraged to outwardly verbalize all thoughts as they proceeded through the problem. If students fell silent for more than 5 seconds, they were prompted by the researcher to continue to think aloud. All sessions were audio recorded for later transcription. The length of the individual think-aloud sessions ranged from approximately 15-to-25 minutes.

In January of 2016, six first-semester ("entering") engineering students participated in the same think-aloud, problem-solving task. We do not report gender information for these students to preserve anonymity. Again, preceding the task, students were asked to solve a warm-up problem. The same procedures for the think-aloud that were used the previous year were followed at this time. All sessions were audio recorded for later transcription. The length of each think-aloud session was similar to those from the pilot data.

Analysis of verbal protocols. We created a categorization scheme to code the verbal utterances from our think-aloud protocols using our theoretical conceptualization of metacognition. We defined metacognition as “knowledge of one’s knowledge, processes, and cognitive and affective states; and the ability to consciously and deliberately monitor and regulate one’s knowledge, processes, and cognitive and affective states” (Hacker, 1998, p. 3). This definition identifies both declarative and procedural components of metacognition (see earlier discussion, What is Metacognition). The elements of each of these components of metacognition then served as the basis for our categorization scheme (see Figure 1).

We added to these a category for utterances that reflected the student’s reading of the problem, a category for utterances that were judged not to be metacognitive in nature but reflected a student’s knowledge of the domain in which the problem was contextualized, and a category that reflected his or her solutions to the various elements of the problem. All categories were operationalized, and these operationalizations were further refined iteratively during the analyses of the verbal data from the first four students. The iterative process followed constant comparison methods in which changes to categories were made and agreed upon through discussion between the coders as new data were reviewed (Bradley, Curry, & Devers, 2007). The final operationalizations are provided in Table 1.

Table 1. *Operationalizations of the Categories of Metacognition*

Metacognitive Control	Determine and Direct Steps:	The statement identifies future steps or procedures that will be taken to solve a specific component of the problem and sometimes indicates when the steps or procedures will be taken. The statement explicitly or implicitly indicates that the problem solver is in executive control or oversight of the problem solving process. The verb is generally future tense or can take the imperative form. The statement contains "I" or "we."
	Allocate Resources	The statement indicates that attentional or cognitive resources are being directed to a specific aspect of the problem or that there is a shift in attention or cognitive resources from one component of the problem to another.
	Set Intensity of Work	The statement indicates that effort is being directed to a specific component of the problem, or effort is being diverted from a specific component, or effort is being maintained.
	Set Speed of Work	The statement indicates that the solution process is being slowed to allow greater focus, hastened to move onto other components of the problem, or maintained.

Metacognitive Monitoring	Identify the Task	The statement identifies a specific component of the problem that needs to be considered. Based on the statement, there is no indication that the identified component will be undertaken, only that it is something that needs to be considered. In general, these statements contain a present tense verb and do not contain an "I" or a "we."
	Check on Current Progress	The statement indicates reflection on progress made or not made on an already identified component of the problem or is considering what additional directions may need to be undertaken to arrive at a solution. Some statements also may indicate that a previously identified component (see Identify the Task) is being revisited or rechecked or that alternatives to the problem solution are being considered. In general, these statements contain a present tense verb and can be in interrogative form and may or may not contain an "I" or a "we."
	Evaluate Progress	The statement indicates an evaluative judgment is made on whether a problem solving process or outcome is adequate, will lead to an expected outcome, needs to be modified or abandoned, or prioritizes problem solving steps in terms of their importance. The evaluative judgment is made after or during the process or the outcome has been obtained. Verb tense can be past, present, or future, and a personal pronoun may or may not be present.
	Predict Outcome	The statement indicates that an anticipated outcome of the problem solving will be forthcoming.
Metacognitive Declarative Knowledge	Cognitive States	The statement indicates a mental state, such a knowing or not knowing, currently thinking, is uncertain or confused. The statement may also indicate the problem solver is carefully weighing aspects of the problem or is engaged in reflection on it. The statement contains "I" or "we."
	Affective States	The statement indicates an affective state, such as liking or disliking something, having fun, or being bored. The statement contains "I" or "we."
	Knowledge of Task	The statement indicates how the problem can be solved, how easy or difficult the problem will be, or how the problem solution will change with changing conditions. The statement contains "I" or "we."
	Knowledge of Strategy	The statement identifies a process or procedure for solving a part or all of the problem, and the process or procedure could be transferred to different contexts. The statement contains "I" or "we."

Domain Knowledge	The statement indicates recall or use of domain-specific knowledge, including both declarative and procedural knowledge, drawn from the domain in which the problem is contextualized. The statement may also indicate the recall of solution processes that can be associated with that domain-specific knowledge.
Solution	The statement provides a solution to one or more of the design elements of the problem. There were eight elements to address: robust construction, costs minimized, construction to withstand a wet climate, increased cargo carrying capacity, more comfortable back seat, motor cycle rack improved, more powerful engine, theft protection of helmets.

Our analysis of the verbal data from each student began with transcribing the audio file from the student's problem-solving session. The transcription for each student was then divided into T-units (i.e., minimally terminable unit; Hunt, 1965). A T-unit consists of a dominant clause and its dependent clauses. Two raters evaluated each T-unit and any disagreements were resolved through discussion. Each rater then independently categorized each T-unit into one of our categories from our categorization scheme. The categorizations between the two raters were statistically compared by computing a Cohen's Kappa. Agreement between the two raters ranged from .61 to .89, with a mean of .76. The categorization procedure also followed an iterative process of constant comparison, and inter-rater agreement between the two raters has increased with each subsequent verbal protocol analyzed. Disagreements were resolved through discussion, and revisions were made to our operationalizations of each category. Examples of the students' utterances and their categorizations are provided in Appendix B.

Results

Analyses of our think-aloud protocols are illustrated in Table 2 for one of our graduating students. We collected similar data for all of our students (both the entering and graduating students), and a summary of these data can be found in Appendix C. As shown in Table 2, each student was analyzed for the number of utterances that were coded into each of the categories from our categorization scheme plus utterances from reading the problem. The percentage of each kind of utterance was then calculated compared to the total number of utterances for that student.

Table 2. *Analysis of Think-Aloud Protocol for One Graduating Engineering Student.*

Summary of Participant #0031		
Statement Classification	Frequency	Percent
declarative: cognitive states	2	1.9
declarative: affective states	0	0
declarative: knowledge of task	0	0
declarative: knowledge of strategy	2	1.9
procedural monitoring: identify task	7	6.8
procedural monitoring: check on current progress	16	15.5
procedural monitoring: evaluate progress	4	3.9
procedural monitoring: predict outcome	0	0
procedural control: determine/direct steps	2	1.9
procedural control: allocate resources	0	0
procedural control: set intensity of work	0	0
procedural control: set speed of work	0	0
reads problem	20	19.4
domain knowledge	18	17.5
solution	32	31.1
Total	103	100.0

Table 3 shows summarized data for all participants. For each participant, we collapsed across categories for types of metacognition, resulting in new categories representing metacognitive monitoring, metacognitive control, and metacognitive declarative knowledge. We added to these domain knowledge, solution, and reading the problem utterances. We then recalculated the percentages of each category for each student. We then averaged these percentages across **Entering Students** (top of Table 3) **and Graduating Students** (bottom of Table 3).

Table 3. *Percentages of Total Utterances for each Major Category Specified in Our Model of Metacognition*

Entering Students (n = 6)	**Metacognitive Monitoring**	**Metacognitive Control**	**Metacognitive Declarative Knowledge**	**Domain Knowledge**	**Solution**	**Reads Problem**
#53	36.1	.8	9.1	18.0	12.8	23.3
#54	21.3	.00	8.5	35.1	10.6	24.5
#58	31.6	1.2	7.6	30.4	17.0	12.3
#50	28.5	.8	18.9	21.1	9.0	21.8
#51	32.7	5.3	10.7	14.2	11.5	25.7
#52	39.7	1.5	18.4	21.5	7.5	11.3
Mean Percentages for Entering Students	31.65	1.60	12.20	23.38	11.40	19.82

Graduating Students (n = 4)	**Metacognitive Monitoring**	**Metacognitive Control**	**Metacognitive Declarative Knowledge**	**Domain Knowledge**	**Solution**	**Reads Problem**
#31	26.2	1.9	3.8	17.5	31.1	17.5
#34	33.6	5.5	10.9	10.0	20.9	19.1
#27	41.0	9.6	10.8	8.4	8.4	21.7
#29	36.9	15.0	13.1	10.0	12.5	12.5
Mean Percentages for Graduating Students	34.42	8.00	9.65	11.48	18.22	18.18

Although the small number of participants to date precludes any statistical analyses, our data do allow a qualitative analysis. Metacognitive monitoring appears to dominate the problem-solving process, accounting for about one-third of the utterances for both entering and graduating students. The two groups were also similar in the percentages of utterances devoted to metacognitive declarative knowledge (i.e., primarily self-referential utterances concerning their cognitive states during problem solving). Both groups also showed about the same percentages of utterances devoted to reading the problem, although entering students showed greater variability, with several of these students showing a great deal of re-reading.

Differences between entering and graduating students are also evident. Our more advanced problem solvers engaged in slightly more metacognitive control of their problem solving, but there were more obvious differences between the groups in their use of domain knowledge and solution utterances. Graduating students devoted a smaller percentage of utterances reflecting their knowledge and use of domain specific knowledge to solve the problem and a greater percentage to providing a solution than entering students.

Conclusions and Future Directions

This evidence-based practice paper focused on identifying the metacognitive skills inherent in self-regulated learning and provided evidence that students at IRE are acquiring these metacognitive skills during their *preparation* as engineers. Our preliminary results have shown that the metacognitive skills inherent in self-regulated learning play a major role in engineering problem solving. Across our entering and graduating engineering students, about 50% of their verbal utterances were categorized as metacognitive. Of that 50%, slightly over 30% reflected metacognitive monitoring of their problem solving. A closer analysis of these monitoring utterances showed that the majority was devoted to identifying components of the problem and checking on their current problem-solving progress. These high levels of metacognitive monitoring are reassuring in that students appear to possess the pre-requisite skill for self-regulated learning. That is, problems must be monitored first before control over them can be exerted. Of the remaining 20% of metacognitive statements, graduating students showed higher percentages of utterances devoted to metacognitive control and slightly lower percentages devoted to expressing their cognitive states when compared to entering students. The differences in metacognitive control may demonstrate that during their preparation as engineers, students are acquiring metacognitive skills to self-regulate by being more directive in their problem solving than their less less-experienced peers; however, with the few number of students involved, this is only a tentative conclusion at this point.

The remaining 50% of students' utterances were non-metacognitive in nature. Graduating students appeared to re-read less than entering students, which may simply reflect their greater knowledge of and familiarity with engineering problems. The two biggest differences between the two groups was in their use of domain knowledge and solution utterances. The former type of utterance, in general, reflected simple recall of knowledge drawn mainly from the domain in which the problem was contextualized. Two examples of these utterances are: “There are materials that are well strong enough to suit those needs.” and “Metal carriers that's probably gonna be what most people use is a metal rack because its sturdy, its cheap, and its relatively rugged.” Entering students appeared to rely on these domain knowledge statements during problem solving to a greater extent than graduating students. Perhaps entering students needed to recall knowledge before they could put it to use in a solution. In contrast, graduating students appeared to have less need to do so and could go directly to a solution, which was reflected in their higher percentage of solution utterances. Their higher percentage of solution utterances also could have resulted simply from having greater knowledge of engineering.

The entering students in this study were in the second week of their studies at IRE when these data were collected. This of course is intentional as we will be collecting “post” think alouds when they are at the end of their programs. These students, thus, had not experienced the same direct instruction and scaffolding of metacognitive activities as the graduating students. While we can only speculate because these are not longitudinal data for a single cohort, it is possible that the differences we see in metacognitive activity are somewhat attributable to the aspects of the curriculum that directly address metacognitive and self-directed learning strategies. The graduating students had experienced four semesters of learning their engineering skills in the context of solving and implementing designs for real-world industry projects. None of their learning occurs in traditional lecture classrooms; thus they are required to develop and exercise metacognitive and self-directed learning skills in order to be successful in their studies. Our data from this study provide preliminary support for the effectiveness of this type of curriculum for developing these necessary skills in our engineering graduates.

Our future work will focus on collecting and analyzing data from students as they solve engineering design problems presented to them at the beginning and end of their programs. By tracking the kinds and sequence of metacognitive and non-metacognitive statements that lead to solutions to the problems and then making within-student comparisons between problem solutions from the beginning and end of the program, we will be able to identify specifically how the engineering program has affected each student’s use of engineering metacognition in their self-regulated learning. We also will triangulate the think-aloud data with students’ self-report interview data to attempt to draw conclusions about what aspects of this unique curriculum were most effective. We also intend to examine the quality of each student’s problem solving by asking a professional engineer to evaluate solution-related statements from the transcripts of each student. By tracking the kinds and sequences of metacognitive and non-metacognitive utterances made by students as they proceed through the problem-solving process and identifying the quality of their solutions for each component of the problem, we will be able to address an essential question about the role of metacognition: Does greater use of the metacognitive processes inherent in self-regulated learning during problem solving produce a higher quality problem solution?

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Appendix A: Think-Aloud Warm-up Problem and Design Task

Verbal Protocol Warmup Problem

This is an exercise for you to practice thinking aloud as you solve a problem. This means that as you solve the problem you will be required to say aloud what you are thinking. If you stop speaking I will remind you to resume speaking aloud as you solve the problem. Please include all the notes and sketches of your solution on the paper below.

Two trains pass through two cities at exactly 2:00 pm Thursday. A Canadian National train carrying iron ore passes through Duluth heading south to St. Paul at a speed of 35 mph. A Union Pacific train carrying new automobiles passes through St. Paul heading north to Duluth on a parallel track at a speed of 45 mph. The track distance between Duluth and St. Paul is 200 miles. At what time of day would the two trains pass one another?

DESIGN TASK (Dixon, 2010)

Instruction

The objective of this engineering design activity is to understand the cognitive process of engineering designers as they solve a design problem. Verbal Protocol Analysis will be used. This means that as you solve the problem you will be required to **"think aloud"** (say aloud) what you are thinking. If you stop speaking I will remind you to resume speaking aloud as you solve the problem. Please include all the notes and sketches of your solution on the sketch pads that are provided.

Duration: 1 Hr

The context

Fonthill is a hilly terrain in the District of St. Mary with narrow tracks and virtually non-existent roads. This area also experiences high amounts of rainfall yearly. There are several communities like Fonthill on this mountainous tropical island. Because of the very poor state of the roads the most frequent mode of transportation are motorcycles. Motorcycles are used to take residents to and from work, market, and school. While the residents see this system of transportation as essential, the government has serious concerns about the safety of the riders and their passengers. The government therefore secured a loan to purchase a fleet of motorcycles that are specially built to handle these rugged terrains. These motorcycles will be leased as taxis to specially trained riders.

Figure 1. The engineering design task (continued)

The design problem

The Honda CRF230 shown on the next page is a cross between a dirt bike and a street bike. Modify the Honda CRF230 so that it is robust enough to handle repeated journeys through these mountainous terrains that are prone to a lot of rainfall annually. The average cost of a new car in this country is about US$25000.00 and the government expects that the cost of this motorcycle will not exceed one third this cost. The motor cycle must also:

- Be equipped with more cargo carrying capacity and at the same time make the rear seating (pillion) more comfortable.
- Have an improved rack or a holding system for carrying packages, books, or a reasonable amount of groceries on the motorcycle. The rack must be non-metallic but of sufficient sturdiness to withstand a rugged terrain, occasional brushing against rocks, and a lot of rainfall.
- Be capable of enough horsepower to climb sections of mountains with slopes of 30 degrees, carrying the rider and the pillion passenger.
- Have a device to prevent the theft of helmets from the motorcycle.

Honda CRF230M .

Figure 1. The engineering design task.

Appendix B: Examples of Various Categorized Utterances

Metacognitive Construct	Metacognitive Process	Examples
Metacognitive Control	Determine and Direct Steps:	So this constraint we don't have to worry until the end. Looking then, so starting another subcategory of cargo capacity to get parameters of what I need to look for. So we also will create the motor. Where we are gonna have to upgrade it.
	Allocate Resources	(No utterances have fallen in this category.)
	Set Intensity of Work	(No utterances have fallen in this category.)
	Set Speed of Work	(No utterances have fallen in this category.)
Metacognitive Monitoring	Identify the Task	So you have to improve the cargo to be able to carry large objects… I guess larger objects. It all comes back to costs of what the initial costs of the bike would be. Rack must be nonmetallic sufficient sturdiness to withstand rugged terrain. And prevent the theft of helmets.
	Check on Current Progress	What else was there? Okay, so I resolved the issue of the cargo carrying capacity is going to be up front. So, I’ve kind of hit those two things, cargo carrying capacity and improved rack for holding stuff. What am I supposed to be doing?
	Evaluate Progress	More upgrades are needed. Lockable helmet is about the least of my worries now. As far as that goes, I think I’m pretty well worked the idea of the problem. The horse power modifications that may or may not be needed.

	Predict Outcome	(No utterances have fallen in this category.)
Metacognitive Declarative Knowledge	Cognitive States	I'm a horrible drawer. I don't know. So, I'm looking at the picture of this motorcycle. Yeah, I don't know what else I would do to it.
	Affective States	I don't know how fun it would be. It's fun.
	Knowledge of Task	These types of things I've had some experience with this with actually altering vehicles. So, I look at the motorcycle and kind of think back to other past. Those are really large constraints that you need to think about, too.
	Knowledge of Strategy	I'd might need to test out a few things to see if it would work well. It's just a lot of the things of like designing and figuring out what I could do if this would be. And I guess probably put it in a 3-D model and maybe put some loads on it and see how it reacts in the virtual world for building it, and applying some real loads to it
Domain Knowledge	So… $25000…. We have a budget of about $8300 to produce this. Metal carriers that's probably gonna be what most people use is a metal rack because its sturdy, its cheap, and its relatively rugged. The average weight of a person is 180 pounds we'll say. So 180 plus 100. $25,000 divided by three.	

Appendix C: Frequency and Proportions of Various Categorized Utterances for 10 Subjects

Frequency of T Units / %										
Participant ID #	#27	#29	#31	#34	#51	#58	#54	#53	#52	#50
Declarative: **Cognitive States**	4/4.8%	7/4.4%	2/1.9%	11/10%	9/8%	7/4.1%	7/7.4%	11/8.3%	42/15.8%	17/12.8%
Declarative: **Affective States**	0/0	1/.6%	0/0	0/0	0/0	1/.6%	0/0	1/.8%	3/1.1%	3/2.3%
Declarative: **Knowledge of Task**	2/2.4%	1/.6%	0/0	1/.9%	3/2.7%	0/0	0/0	0/0	0/0	1/.8%
Declarative: **Knowledge of Strategy**	3/3.6%	12/7.5%	2/1.9%	0/0	0/0	5/2.9%	1/1.1%	0/0	4/1.5%	4/3%
Procedural Monitoring: **Identify Task**	11/13.3%	16/10%	7/6.8%	9/8.2%	9/8%	17/9.9%	4/4.3%	6/4.5%	14/5.3%	10/7.5%
Procedural Monitoring: **Check on Current Progress**	14/16.9%	32/20%	16/15.5%	24/21.8%	24/21.2%	21/12.3%	8/8.5%	35/26.3%	81/30.6%	24/18%
Procedural Monitoring: **Evaluate Progress**	9/10.8%	11/6.9%	4/3.9%	4/3.6%	4/3.5%	16/9.4%	8/8.5%	7/5.3%	10/3.8%	4/3%
Procedural Monitoring: **Predict Outcome**	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
Procedural Control: **Determine/Direct Steps**	8/9.6%	24/15%	2/1.9%	6/5.5%	6/5.3%	2/1.2%	0/0	1/.8%	3/1.1%	1/.8%
Procedural Control:	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

Allocate Resources										
Procedural Control: **Set Intensity of Work**	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
Procedural Control: **Set Speed of Work**	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/.4%	0/0
Reads Problem	18/21.7%	20/12.5%	20/19.4%	21/19.1%	29/25.7%	21/12.3%	23/24.5%	31/23.3%	30/11.3%	29/21.8%
Domain Knowledge	7/8.4%	16/10%	18/17.5%	11/10%	16/14.2%	52/30.4%	33/35.1%	24/18%	57/21.5%	28/21.1%
Product	7/8.4%	20/12.5%	32/31.1%	23/20.9%	13/11.5%	29/17%	10/10.6%	17/12.8%	20/7.5%	12/9%
Totals	83/100%	160/100%	103/100%	110/100%	113/100%	171/100%	94/100%	133/100%	265/100%	133/100%