The Development of Engineering Students' Metacognitive Skills in Informal Engineering Learning Activities

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Introduction

The ability to analyze and evaluate one's own thinking and acquisition of knowledge and skills, or metacognition, is an important set of skills for engineering students to acquire. Metacognition is simply defined as "thinking about thinking" or "cognition about cognition" [8]. It is awareness of one's learning processes and regulation of one's learning behaviors [8]. In this paper, we will address two types of metacognitive skills: metacognitive knowledge and metacognitive regulation. Flavell [8] described metacognitive knowledge as an individual's knowledge about their own cognitive processes; metacognitive regulation is a process in which individuals monitor, regulate and evaluate cognitive activities to attain particular cognitive goals [25]. Metacognitive skills are related to learning. Students who understand how to apply metacognition to their learning had a better understanding of learning and were more successful [1, 9, 17]. Specifically, students' self-awareness of their learning processes facilitated learning and performance [2]. In addition, students' application of metacognitive skills in practice supported students' learning within different contexts and improved their adaptive capabilities within those contexts [23]. Because adaptive capabilities are critical within the engineering workplace, it is important that engineering students learn metacognitive skills necessary to develop adaptive capabilities. The purpose for this work is to examine students' statements about their experiences within engineering competitions and a service-based learning project identifying their metacognitive reflections about their participation in these informal learning environments.

Background and Motivation

The conceptualization of "thinking about thinking" has evolved since Flavell [8] first discussed metacognition. Researchers have agreed that metacognition consists of knowledge of cognition and regulation of cognition [8, 19, 20, 25]. Knowledge about cognition describes individuals' self-knowledge, knowledge about strategies, as well as appropriate application of different strategies in practice. Knowledge about cognition consists of three types of knowledge including declarative knowledge, procedural knowledge and conditional knowledge [10]. Regulation of cognition indicates that individuals are capable of planning, managing information, monitoring, debugging and evaluating [10, 20, 24, 25].

In engineering practice, researchers have found significant differences between novices and experts in their application of metacognitive skills. For example, expert engineers were able to analyze situations, apply strategies and monitor themselves better than novices [21]. Importantly, metacognitive skills can be taught. Engineering students can become experts by methodically learning metacognitive skills. For example, by mastering metacognitive skills, engineering students within diverse contexts improved applied problem-solving skills and increased their reflections about their learning [3]. Thus, providing opportunities for engineering students to cultivate metacognitive skills within curricular and co-curricular learning opportunities may act as a means for students to become qualified engineers more efficiently.

Industry practitioners in engineering increasingly expect that graduates should obtain required technical and professional skills and apply the skills efficiently [7, 12]. In addition to expected

technical skills, such as experimentation, and professional skills, such as communication and teamwork, employers also expect students to have acquired cognitive skills, such as critical thinking, and metacognitive skills, such as reflection, understanding learning objectives within the work environment, and self-evaluation [3, 6, 7]. To foster successful engineers, engineering students require learning environments where they will have opportunities to develop metacognitive skills.

Compared to traditional lecture-based engineering education curricula, experiences with informal learning activities, such as engineering competitions, offer students authentic work environments to gain hands-on experiences and to develop and practice metacognitive skills [13, 16]. Informal learning activities provide students with opportunities to situate learning within non-curricular settings, facilitating fit within the engineering community [11]. From the situated perspective, students have lived experiences of different identities while they work on various informal learning tasks [11], which increased students' comprehension of actual engineering work content and work approach.

Prior research has focused on classroom interventions to cultivate engineering students as metacognitive learners. For example, Cunningham, Morelock, & Matusovich [5] taught students to understand what metacognition is and why it is important. They also prompted students to answer reflective questions, which facilitated students' self-evaluation about their exam performance. In another study, Mazumder [18] asked engineering students to use an online metacognitive tool to self-assess how their knowledge and confidence levels changed over the course [18]. These studies prompted students to understand and apply metacognitive skills within classroom settings. In contrast, the current study explored engineering students' metacognitive skills through their participation in informal learning activities. Research about metacognition in engineering in informal learning environments is nascent. This paper will add to the growing body of research about metacognition within informal learning experiences in engineering.

Conceptual Framework
Although there are multiple theories discussing metacognition [4, 8, 14], there is a common view that metacognition includes knowledge of cognition and regulation of cognition. The current study employed Schraw's work about metacognition [25] as the conceptual framework because of its comprehensiveness and alignment with the current consensus about the components of metacognition. Schraw and Dennison [24] validated the Metacognitive Awareness Inventory (MAI) which provided the operational definitions for our component categories of metacognition.

The components of metacognition, knowledge about cognition and regulation of cognition, contains subcategories [24, 25]. Knowledge about cognition consists of declarative knowledge, procedural knowledge and conditional knowledge. Declarative knowledge describes individuals' knowledge about themselves, such as their abilities, skills, or intelligence, and their knowledge of strategies or certain content before they use them, as well as their knowledge of environments or contexts. Procedural knowledge is the knowledge that an individual understands *how* to use appropriate strategies. Conditional knowledge describes individuals' knowledge of *when and why* to use certain strategies within a given situation or set of circumstances.

Regulation of cognition includes planning, information management strategies, monitoring, debugging strategies and evaluation. Planning addresses goal setting and planning of integrating resources before learning. Information management strategies describes strategies that individuals utilize for efficient information processing. Comprehension monitoring is a personal assessment of one's learning or strategies application. Debugging strategies are the strategies that individuals use for correcting errors and miscomprehension. Evaluation is individuals' analysis of the effectiveness of their use of strategies use and their performance. The current study applied these operational definitions of metacognition of Schraw and Dennison [24] to examine engineering students' metacognitive skills within two informal learning environments.

Research Questions

This current study explored specific metacognitive skills that engineering students demonstrated in their participation in two types of informal learning activities, engineering competitions and a service-based learning project. We examined students' discussions of their experiences to address our research question: What metacognitive skills do engineering students discuss about their participation within the engineering competition or service-based learning project?

Method

This qualitative study took place in a large university, with a well-subscribed engineering program, in the eastern section of the United States. Multiple types of informal engineering opportunities existed at that university at the time of this study. We studied students who participated in two types of informal learning activities, which included a service-based learning project, such as Engineers Without Borders (EWB), and engineering competitions, such as Formula SAE and IAM3D. The Institutional Review Board approved the study.

Participants

Forty-seven undergraduate students who participated in the informal learning activities were invited to participate in the study. Eighteen students agreed to be interviewed. Three individual interviews with the student leaders who coordinated teams in Formula SAE were conducted. Fifteen focus groups interviews were conducted with students who participated in EWB, Formula SAE and IAM3D.

Instruments and Data Collection

Metacognition is a complex construct. As a complex construct, it is difficult to directly measure metacognition. Metacognition refers to both knowledge and regulation about cognition. Several methods exist that have been used to examine metacognition, such as self-report, a think-aloud approach, or interviews and questionnaires [19]. In the current study, participants were interviewed and prompted to recall and discuss their experiences in the two types of informal learning environments, service-based learning project and engineering competition. We used the students' statements to examine their self-reported application of metacognitive skills [24, 25].

Interview protocol focused on students' experience of the given project within the informal environment, as well as their understanding about their learning through this non-curricular setting. Open-ended questions were developed to encourage students' natural statements about their experiences. Sample interview protocol included: (1) Tell me a little bit of what you do right now, what's your primary responsibility? (2) So what does a typical day for you look like

right now? (3)What helps you the most to learn the skills that you need for the project right now? (4) How often would you say that you use things that you learn in your classes? (5) Would you say it's mostly the content of the class, or the experience of the class that helped the most? (6) Can you walk me through how you would solve a problem, just an example? Interviews were transcribed for preparing the work of coding [22]. We did discern that metacognitive skills could be examined as participants' learning outcomes from such environments.

Data Analysis
We applied Schraw's work about metacognition [24, 25] as a conceptual framework, deriving a priori codes from their operational definitions of metacognition. First, we distinguished transcript content of engineering students' knowledge about cognition and their regulation of cognition and processed this as initial coding. After indicating related quotes under these two main categories, further coding was applied, which employed the operational definition of metacognition component categories [24] as code categories in the current study. We applied the a priori codes for declarative knowledge, procedural knowledge, and conditional knowledge for knowledge about cognition. Thus, knowledge about cognition was coded according to students' description of their understanding about themselves, knowledge about personal skills or learning strategies, as well as their comprehension about when to use specific strategies for certain activity tasks. For regulation of cognition, we applied the codes of planning, information management, monitoring, debugging, and evaluation. Thus, regulation of cognition was coded based on students' descriptions about how they implemented or adjusted their strategies or skills while they were participating in activities. Quotes within each sub-themes of both categories were classified and sorted.

Results
Evidence of engineering students' metacognitive awareness was identified from their retrospective description of learning experiences in their participation of the informal learning activities. Based on classified quotes, we analyzed the specific metacognitive skills the engineering students discussed related to their experiences in these informal learning activities.

Knowledge about Cognition
The knowledge about cognition was discussed by three main sub-themes: declarative knowledge, procedural knowledge and conditional knowledge. Declarative knowledge was coded based on students' understanding and familiarity about themselves including their ability, skills, situation, and prior factual knowledge. For example, students analyzed his/her lecture-based learning situation, and the state of his/her skills within the competition: "Especially in electrical, what we do is almost entirely theory, but the few hands-on work, like circuit boards or stuff like that. But like here it's actual hands on. Like here's a problem. You gotta assess it. You analyze it. And then, you implement it all the way through, like beginning to end. That's the best experience."

We identified students' procedural knowledge on the basis of their knowledge of the process or procedures of completing certain tasks, and the purpose of particular tasks, as well as their knowledge obtained through discovering and practicing. For instance, one student clearly explained his/her procedural knowledge: "After conceptual thinking, it would be a structured approach. You would have to, kind of like, if you were writing a paper, how you make an outline first. That's kind of like, one thing that I would do. Of course, I would have to calculate this and

then this. Basically, what I would do first is, how do I get to the... final life of this fly wheel? And then there is this series of equations that I need, and then to get those equations you could do a series of steps before that."

Conditional knowledge is more about students' knowledge of when and why to use certain knowledge, strategies or skills under diverse conditions. For example, students said: "From there, we figured out the print times and volume size, cause a large part of the competition is reducing your print time designing for AM. So we really wanted to score well in those categories, so …we had two final CAD products, and we took the one that had a smaller print time."

Regulation of Cognition
According to Schraw and Dennison's [24] operational definition of the category of regulation of cognition, we mainly focused on the sub-themes of planning, information management strategies, comprehension monitoring, debugging strategies, and evaluation. Planning here includes not only planning, but goal setting by allocating resources. For instance, students talked about their planning: "But I have access to a 3d printer, and CAD stuff, so when I have a new idea for a … design, I just print it out, and 'oh this doesn't work' and I made this change and I try again." Students also discussed goal setting for particular task: "I remember when we were trying to come up with the design for the landing gear, how to attach it to this body. We were like we need landing gear here, but we don't have any material there, let's just draw a bar over there. And we did, connect point a to point b."

Students who processed, summarized and elaborated the required information were coded as information management strategies, such as: "There are things that are based on most quadcopter styles, and there were certain considerations that we had to come up with – so one of the things [in the] competition is why is additive manufacturing a good thing for this design. So we tried to – you can change the density of some of the plastics, so that's why we have the kind of the little rubbery bits, because it's meant to I think absorb some of the vibrations."

We focused on how students access their learning or strategy. For example, one student assessed his/her usage and learning of one technique: "For me in my classes, on the technical side, most of the analysis we're doing is just simple mathematical analysis of simple objects, whereas in this competition we've been doing a lot of FEA so, it's a whole different technique than what I'm used to in my courses."

The debugging strategies were coded based on whether students showed their skills on correcting any errors occurring by their participation, or on improving the effectiveness of their tasks. Students provided some examples: "Since we had members experienced with programming, we were expecting to go and manipulate the program to what we needed. Unfortunately because of how they programmed it, we could not do that, and weren't able to really do anything with it which made it harder for driving with the joysticks. We were only able to use one joystick instead of two, which made driving really hard, so any possible way of more time and manipulation for programming would be a lot better."; Another student stated, "I was fixing the points, so that, I was doing some iterative analysis to see if we could get it down to 0.8 instead of 1."

The last metacognitive skill we examined was self-evaluation of students' performance or effectiveness of their learning. For instance, one student stated: "…with the projects, as the write up gets finished, you go back, and you think, do I need to add more to this, have I really justified the way that I did it. So the projects are constantly being updated, they're kind of a living project"

Discussion
The results of the current study demonstrated that in the experiences of informal learning activities, engineering students showed specific metacognitive skills during their learning process, which answered our research question: What metacognitive skills do engineering students show within the informal learning activities? We captured the metacognitive skills students presented through their retrospective statements about their participation in informal learning activities. Their metacognitive skills fell into two major categories: knowledge about cognition and regulation of cognition. Students showed their knowledge about cognition in declarative knowledge, procedural knowledge and conditional knowledge; students demonstrated their regulation of cognition in planning, information management strategies, comprehensive monitoring, debugging strategies and evaluation.

In completing the tasks in the informal learning environments, students understood the knowledge of cognition and then regulated their cognition. They understood the effectiveness of specific strategies in applying to certain tasks. Moreover, they also understood when to utilize particular strategies properly to solve problems. Students allocated their knowledge of self, knowledge of strategies, also engineering content knowledge to regulate their cognition in order to proceed to complete tasks within the informal learning activities.

Different from the traditional lecture-based engineering education, the informal learning activities in this study appeared to provide students with authentic practice environments as a platform for students to think metacognitively. Students learned through practice. Compared to the participation in formal didactic teaching settings, students in informal learning activities are exposed to the engineering community and networking which motivate students to learn engineering as a holistic industry [11]. The micro-level or student skills focus of this study provided an opportunity to understand how students' considered their strengths and weakness, which could potentially help students to examine their personal goals. Students had the opportunity to reflect on the accuracy of task analysis and strategic planning in authentic engineering environments [16]. Thereupon, they have opportunities to be self-directed and to evaluate their learning outcomes in informal learning activities [11, 15].

Limitations and Future Study
The current study examined students' retrospective statements in interviews which might have addressed metacognition only on a surface level. We did not examine how students' metacognitive knowledge interacted with their metacognitive regulation. Another limitation of the current study was the issue of generalizability. The current study took place in certain place and interviewed students who participated in the informal learning activities of competition and service learning. Also, all the participants were willing to participate in informal learning activities so that they all had relatively high motivation for participating in the activity, and

perhaps the study. Therefore, there was not enough evidence to generalize the results to all informal learning activities and all informal learning participants.

Conclusion

Metacognitive skills are important qualities of successful engineers. As a non-curricula learning approach, informal learning activities, such as competitions and service based learning, can provide students authentic environments to develop their metacognitive skills. The current study used qualitative methods to examine specific metacognitive skills students discussed within competitions and service learning projects. Results identified particular metacognitive skills that students exhibited in informal learning activities, including the knowledge of cognition, such as, declarative knowledge, procedural knowledge and conditional knowledge, as well as the regulation of cognition, such as planning, information management strategies, comprehensive monitoring, debugging strategies and evaluation.

Acknowledgements

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