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THE SELF-MANAGEMENT OF COGNITION IN A TEAM-BASED ENGINEERING DESIGN PROJECT: A Case Study

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Despite differences in educational programs offered by various engineering schools, all engineering education puts its emphasis on students' ability to apply their knowledge of mathematics, science, and engineering. Engineering students are expected to demonstrate their ability to apply that knowledge through various activities such as problem solving, design, and experimental activities during their study. In professional engineering practices, engineers are challenged to solve real-world problems that generally involve certain levels of task ambiguity and complexity. Moreover, they are often obligated to work in a team-based environment. Because of these requirements, engineering students should acquire these skills and demonstrate their ability to apply these skills during their studies.

Working on an open-ended task such as designing an engineering artifact is indeed a rich learning experience for students, although they generally receive little direct guidance and instruction from their professors. In order to be successful on such a task, students need to set reasonable goals for themselves and adopt intrinsic standards for success so that they will be able to solve problems strategically. Many studies (Brown, Bransford, Ferrar, & Campione, 1983; Efklides, 2002) have found that students' cognitive and metacognitive skills (i.e., monitor and control one's own cognitive processes) play an essential role in such problem solving processes.

Engineering students who engage in an open-ended task, whether they are working alone or in a team, have some sort of plan or method in mind to solve the problem. This problem-solving method may come from the knowledge and skills these students gained from their earlier design classes or it may be generated from their common sense of thinking that is translated into a working behavior and strategy. Whether implementing strategies learned from previous classes, or executing pure common sense, engineering students are expected to use their metacognitive knowledge and metacognitive experiences (Flavell, 1979) to successfully solve whatever tasks they are engaging in. Metacognitive knowledge is a term that refers to the knowledge students retrieve from memory that affects the course and outcome of cognitive enterprises. Metacognitive experiences comprise students' ideas, feelings, judgments, and metacognitive knowledge evoked during problem solving. In other words, metacognitive experience is "items of metacognitive knowledge that have entered consciousness" (Flavell, 1979, p. 908). Students' metacognitive knowledge and experience are believed to be one of the contributing factors that influence students' learning accomplishments.

Many studies have been conducted on metacognition to investigate its impact on learning in various learning contexts such as reading (Brown, Bransford, Ferrar, & Campione, 1983) and problem solving in mathematics (Efklides, 2002). In those studies, researchers found a relationship between use of metacognition and performance. Efklides (2002) found that feelings of familiarity, difficulties, confidence, and satisfaction are interrelated, and they are all considered as metacognitive experience, which is inferential in nature.

Since most professional design engineers work in a team-based environment, the success of projects very much depends on the effectiveness of their team management. Professional engineers know that engaging in a design project in a team often requires engineers to manage more than just their own individual technical expertise. They need to manage their organization and team work skills as well. To do so, they are often required to create a working environment that facilitates collaborative activities so they can build and monitor their teamwork. Although the intention of doing team-based activities in academic setting is to promote richer learning experiences for students, Dunbar (2000) argues that several studies find that it is not always the case. As a team, students are expected to be able to use their knowledge, skills, time, and other available resources effectively so their work objectives can be accomplished. This study attempts to further our understanding of the use metacognitive skills of students who engage in an open-ended team-based design project.

In this study, we are about to learn how a group of engineering students exercised their self-management of cognition, through the way these students planned, evaluated, and regulated their cognitive activities, during the design process to build an engineering artifact. Using Paris and Winograd’s lens of self-management of cognition, two research questions were constructed to guide this instrumental case study. They were:

1. How did individual members of the team execute their meta-cognitive ability as reflected in the way they plan, regulate, and evaluate any task they encounter throughout the project time?

2. How did the way they plan, regulate, and evaluate any encountered task fit together as the team evolved their design?

Metacognition and Its Forms

Although experts offer many different definitions and models, metacognition remains a “fuzzy concept” because experts classify any cognition that might have relevance to knowledge and thinking as a *metacognition* (Paris & Winograd, 1990). Experts in cognition have varying definitions of metacognition and many of those definitions overlap. Although numerous definitions exist, it is clear that metacognition is a fundamental tool that enables learners to take control of their own cognition. As a result, they tend to learn better (Bransford, Brown, & Cocking, 1999; Chambres, Bonin, Izaute, & Marescaux, 2002). Experts also classify the features or components of metacognition differently and again some of those features overlap. Flavell (1979) stresses that the phenomena of metacognitive knowledge consists primarily of factors of person, task, and strategies. The factor of person encompasses everything that learners could come to believe about the nature of themselves and other people as cognitive processors. The factor of task and the factor of strategies refer to the information available that leads to learners’ understanding of the task demands (i.e., goals), and learners’ understanding of strategies to achieve those goals, respectively.

The application of one’s metacognitive skills can be observed through what that particular person does for a particular given task. Brown (1978) identifies metacognition through activities such as planning, monitoring, and revising. Paris and Winograd (1990) offer a more comprehensive view where metacognition can be observed through two essential features of metacognition; (a) cognitive self-appraisal and (b) cognitive self-management. These two metacognitive features involve cognitive and motivational issues such as skill and will, which are interwoven with one another (Corno & Mandinach, 1983), and are shareable among people (Paris & Winograd, 1990) and influenced greatly by the social aspects of the situation (Chambres, Bonin, Izaute, & Marescaux, 2002). These aspects include affective and motivational characteristics of thinking that often lead to situations where students are less likely to invoke complex cognitive and metacognitive routines to improve learning.

Students' motivational components such as students' intrinsic goal orientation, self-efficacy, task value, and learning beliefs play an important role in self-directed learning. According to Pintrich, Smith, Garcia, and McKeachie (1991), intrinsic goal orientation concerns the degree to which the student perceives himself or herself to be participating in a task for reasons such as challenge, curiosity, and mastery. Unlike goal orientation, which refers to the reason why the student is participating in the task, task value refers to the student's evaluation of how interesting, how important, and how useful the task is. Self-efficacy is a strong belief about the student's ability and confidence to perform the task. This expectancy leads to a positive influence on the individual's willingness to initiate difficult tasks (Corno & Mandinach, 1983). The last motivational component, learning belief, refers to the students' belief that the outcomes are contingent on their own effort (Corno & Mandinach, 1983; Pintrich, et al., 1991). Although many aspects influence learner's metacognitive abilities, like other knowledge, metacognitive understanding develops with age and experience (Garner & Alexander, 1989) and is an ongoing process of progressing through deeper insights or realizations that, in turn, lead to awareness or conscious understanding of self as agent (McCombs & Marzano, 1990).

Self-appraisal in learning refers to learner's personal judgment about his or her own ability to meet a cognitive goal. When a student is asked to calculate the volume of a triangular-shaped birthday cake, he or she may immediately wonder if he or she had enough knowledge (i.e., declarative, procedural, and conditional knowledge) to answer such question. Self-appraisal is about "judgments about one's personal cognitive abilities, task factors that influence cognitive difficulty or cognitive strategies that may facilitate or impede performance" (Paris & Winograd, 1990, p. 17). Furthermore, Paris and Winograd argue that self-appraisal often relates to static judgments, as students are asked to assess knowledge or gauge ability in a hypothetical situation. This self-appraisal is often called knowledge of self (Flavell, 1979), in which students activate their relevant knowledge about their own strengths and weaknesses pertaining to the task, as well as their motivation for completing the task (Pintrich, 2002).

In contrast, self-management refers to maintaining executive control that will indicate "how metacognition helps to orchestrate cognitive aspects of problem solving" (Paris & Winograd, 1990, p. 18). This self-management issue, which Wixson (1983) refers to as an executive control of behavior, relates to processes that involve evaluation, planning, and regulation. Self-management skill refers to students' abilities to plan before they handle a task and make necessary adjustments and revisions during their work, which consequently has direct implications for students' performance. Three skills are commonly used to indicate the presence of students' self-management: (a) their ability to plan, (b) to regulate, and (c) to evaluate their learning. Planning involves activities such as setting goals, analyzing tasks, and selecting strategies to achieve specific goals. Regulating refers to the fine-tuning and continuous adjustment of learners' cognitive activities. Evaluation refers to assessing learners' current knowledge state. Evaluation occurs continuously: before, during, and after a task.

Method

The purpose of this study was to examine learners' self-management of cognition by observing a group of four undergraduate engineering students (i.e., the Orange Team) exercising their executive control over behavior during their work on their senior design project class (MIE 470). MIE 470 is one of the major capstone design courses prescribed by the mechanical engineering department's curriculum at the University of Illinois at Urbana-Champaign.

Design Task and Context

This team's task was to design and build a hydraulic bicycle. This project was funded by an external organization referred to in the document as PHC, which is a leading diversified manufacturer of motion and control technologies and systems. As part of the funding agreement, this team, and other teams from different universities that also received this hydraulic bike funding, had to participate in a hydraulic bike race competition upon completion of the project. The competition was separated into two separate races: an endurance race and a sprint race. The endurance race consisted of completing three laps on a four-mile circuit course, while the sprint course consisted of a one-tenth of a mile straight away.

Unlike a regular bicycle, a hydraulic bike replaces a mechanical drive system with a hydraulic transmission and therefore, there is no direct connection between the chain-wheel and the free-wheel cogs. Like riding a regular bike, the rider needs to pedal the bicycle's crank gear which is connected with a chain to a pump. The rotating chain rotates the pump's driving shaft. Power is supplied to the pump's driving shaft, which displaces fluid through piping to the motor. Fluid flows through the motor and generates power to turn the free-wheel of the bicycle. The outgoing fluid is then distributed back into a reservoir, which provides fluid back to the pump. Both pump and motor are not electric, but rather they are mechanical motor and pump.

Despite technical engineering design requirements, the prototype of the hydraulic bike had to satisfy realistic constraints such as economic, environmental, sustainability, manufacturability, ethical, social, political, and health and safety issues. The funding organization was interested in exploring the use of small-scale hydraulics to improve the efficiency of the existing bicycle design. As far as the design processes and outcomes, this team had to comply with project's requirements and design criteria set by the department as well as the funding organization.

Since MIE 470 is a graded course, a teaching professor was assigned to this team and functioned as both the project adviser and project evaluator. This team was required to write and present the team's project proposal to the project advisor and the funding organization. Upon their approval, this team was then expected to carry out and complete the project within one semester. Periodically throughout the duration of the project, this team presented the progress of project to the advising professor and funding organization. The course grade was given to each student based upon the team's performance in preparing, executing, and completing the design project. Before the semester ended, the team prepared the final project report and presented the design product to the advising professor.

Engaging in an open-ended activity such as this design project, which commonly acquires minimal instruction and guidance, required these students to rely heavily on the execution of their self-management of cognition. Motivation (Corno & Mandinach, 1983) becomes one of the important factors in achievement for such a project, and quite often, having reasonable goals and intrinsic standards are not enough for achievement. It is the interaction between the context and what the students bring to the context that affects student motivation (Linnenbrink & Pintrich, 2002).

To understand how self-management of cognition was used in this project, the various activities of the four students were evaluated throughout the project. Their activities were based upon two distinct types of tasks: individual and team management, and design processes. Team and individual management was more closely related to team and administrative-related tasks, while design processes focused on technical design-related tasks.

Participants

A team of four students (i.e., the Orange team) were selected for this study. These students had voluntarily accepted to work on this funded project as their senior design project. This particular team consisted of four senior mechanical engineering students, three males (i.e., Brian, John, and Alex) and one female (i.e., Linda). All names are pseudonyms. This team was one of 33 other teams who participated in the MIE 470 in the spring semester. While taking MIE 470, these students were also taking several other courses (i.e., three or four other classes) to fulfill their mechanical engineering degree requirements. Prior to this project, no team member knew *all* of the other individuals in the team. However, some of them knew individual teammates from past classes.

There were two reasons why this team was selected for participation in the study. First, the project this team was working on was funded by PHC. Since the project was funded by an external party, students were expected to be more accountable with their work and the hydraulic bike they would produce. Second, according to the team's co-advising professor, who has extensive experience in advising engineering teams, the Orange Team consisted of students who had good academic performance (i.e., Cumulative GPA ≥ 3.00) and moreover, these students had off-campus work experience through internship programs during their college year. It was expected that good academic standing students with some off-campus work experience, would have adequate knowledge and skills to engage in an engineering design project collaboratively in a team-based environment, like this design project.

Procedure

This study was an instrumental case study (Stake, 1995) that examined the design process in a work team through careful observation of each team member's ability to exercise his or her executive control over behavior during the project. This study employed a naturalistic design in that these students were observed through their individual and group activities. It was expected that this approach would reveal how engineering students exercise their metacognition abilities while engaging in a team-based project.

Data Collection

To gain a better understanding of the student design activity and processes several sources of information were accessed. Throughout the design process, interviews were conducted with each member of the team, observations were made at the team's working laboratory, accessing team communications were accessed (i.e., emails and shared Netfiles[1]), and individual logbooks were read. For anonymity, interviewee names were coded using his or her pseudonym. The purpose of the interviews was to obtain information on how students, individually and as a team, evaluate, plan, and regulate their cognitive activities. The gathered information from interviewing and other resources, such as shared electronic files that were posted in the university Netfiles system, student-student emails, student-professor emails, logbook, status reports, presentations, and meetings, were categorically aggregated and directly interpreted (Stake, 1995). In other words, interpretations were made through individual instances as well as through aggregation of instances until a clearer picture of understanding emerged about the Orange Team's hydraulic bike design process.

Instrumentation

Four control-of-self skills were quantitatively measured in this case study through motivation scales of the Motivated Strategies for Learning Questionnaire (MSLQ) designed by Pintrich, Smith, Garcia, and McKeachie (1991). The internal reliability coefficients for each motivational component are high: Intrinsic Goal Orientation (i.e., $\alpha = .74$), Task Value (i.e., $\alpha = .90$), Control of Learning Beliefs (i.e., $\alpha = .68$), and Self-Efficacy for Learning and Performance (i.e., $\alpha = .93$) The scale correlations with the final

[1] Netfiles is an online service that allows University of Illinois at Urbana Champaign (UIUC) faculty, staff, and students to access their files from anywhere in the world.

grade of this test instrument are statistically significant (i.e., Cronbach's alphas of .52 to .93) which demonstrate predictive validity.

The motivation aspects measured through MSLQ were students' intrinsic goal orientation (4 questions), students' task value (6 questions), students' control beliefs (4 questions), and students' self-efficacy for learning and performance (8 questions). These four motivation components were purposely selected because they represent the value and expectancy components of student's motivation (Pintrich, Smith, Garcia, & McKeachie, 1991). The intrinsic goal orientation and task value are two value components of motivation, while control beliefs and self-efficacy for learning and performance are the expectancy components of motivation. These questions were only parts of the MSLQ instrument and they were asked in the same order as its original complete version. The instrument uses a seven point Likert scale from "not at all true of me" (i.e., scale of 1) to "very true of me" (i.e., scale of 7). For each of those four motivational components, an averaged score was calculated and assigned to each team's member. Those four scores for four motivational components were then averaged and assigned to each team's member. MSLQ scores of all team members were compared.

Data Analysis

Two types of data collected in this study were analyzed differently, statistical and qualitative interpretations. The MSLQ data, scores from each motivational components item (i.e., intrinsic goal orientation, task value, control beliefs, and self-efficacy for learning and performance) of each team member were averaged. To interpret these averaged MSLQ data, Pintrich, Smith, Garcia, and McKeachie (1991) suggest that students should be considered doing well (i.e., good motivation that are able to successfully support learning) if their scores are above 3. Since MSLQ was not used as the primary data source, therefore, these students' averaged scores were only be used to compliment our data analyses from interviews, email messages, team's final project report, and observations. Data from recorded interviews, email messages, team's final project report, and notes from observations were qualitatively analyzed by sorting them into categories to find the common themes that indicated the students' self-management of cognition activities (i.e., planning, evaluating, and regulating). To minimize error in interpreting these qualitative data, whenever needed, data from one source was often triangulated with other relevant data sources.

Findings

Victor Hugo, one of the best-known writers in the 19^{th} century, once said "A man is not idle because he is absorbed in thought. There is a visible labor and there is an invisible labor." Perhaps, he was expressing a situation like these four mechanical engineering students had experienced in their hydraulic bike design project. After being with these four students for 14 weeks, conducting more than 10 hours of field observation, two individual interview sessions with each of them, reading four individual journals, and reading 45 email messages, a clear picture about the process and the dynamic of this team in designing and building an hydraulic bike could be drawn. There was sufficient evidence that these students had applied their self-management of cognition skills in numerous activities from the standpoint of individual and team management as well as design processes.

All team members had above 3.00 in all four motivational scores (i.e., intrinsic goal orientation, task value, control beliefs, and self-efficacy for learning and performance) measured by the Motivated Strategies for Learning Questionnaire (MSLQ) instrument. According to the MSLQ manual, if a student has an average score of 3.00 or above in all motivational components that particular student could be considered as having adequate motivation (Pintrich, Smith, Garcia, & McKeachie, 1991). Using this guideline, all team members had an “adequate” to “high” motivation for this MIE 470 project. However, when comparing these four averaged scores for all four motivational components, Linda had the lowest score in the team. She was relatively low on the intrinsic goal orientation and the task value. Her averaged score was 3.96 and it was below the average of the team’s averaged score (i.e., 5.18).

Team and Individual Management

This study found that most of the tasks were conducted with the spirit of colleagues where no one had more authorizing power than others. This made the working environment less structured and more egalitarian in nature. No line of authority existed in this team as each team member shared his or her responsibility to make the team function and ensure the project was completed on time.

Although this team did not specifically assign any particular role to its members, specific responsibilities of each individual member were stated in the project proposal. It was clearly stated in the project proposal that John was responsible for the implementation or integration of the hydraulic circuitry into the bicycle framework and Brian was responsible as the liaison officer to any outside group such as hydraulics and bike part manufacturers. Linda and Alex had their own roles in this project. All four team members unanimously confirmed that it was never written as intended, although some of those members actually assumed the roles as stated in the proposal. These students considered the inclusion of these specific individual' roles for each team-member was simply to fulfill the course requirement. As the project was progressing, each team member became familiar with the tasks associated to the project and knew what needed to be done. Specific individual responsibilities became present, although it was still informally assigned.

It was apparent during the first three weeks of the project that this absence of work coordination and individual work role had created some confusion to the team. It started from the situation where no one in the team made an effort to follow up on any of the team's resolutions to the situation where no work monitoring was conducted because everybody in the team was busy and had been intensively involved in one particular task. Linda conveyed her thoughts on this issue by saying, "…after we discussed the process, we kind of just let it go…so it was the execution of the activities according to the timeline that was not going smooth." She also said that if the project needed to be managed from the outside, it should be done by people who were not involved in the design and testing because "people who are involved in the design and testing knew what was going on so they would not constantly manage the process in the managerial way, but rather more like a colleague-type of way." Besides Linda, John had also expressed his concern on this team management issue. Both of them seemed to have some sort of procedural knowledge of how they, as a team, should have functioned. The other two members, Alex and Brian, never talked about the issue.

It was interesting to learn that although it was lacking clear team leadership, and the team had some expectation about how the team should have been managed, no immediate corrective action was taken in regard to this leadership concern. Apparently, this team was more focused on the efforts of getting all the design tasks (i.e., building a working hydraulic bike) completed and all the course requirements fulfilled than trying to improve the team's management. These students, individually, monitored their team's work progress, and they knew what had gone right, and what had not gone so smooth and therefore, things needed to be corrected. But, despite all that, this awareness seemed to end there without much follow-up to improve the teamwork. Perhaps, this working condition refers to what Flavell (1979) argued about the misalignment between team's metacognitive knowledge and metacognitive experience. The fact is that knowing a strategy does not necessarily manifest itself into actions.

As generally exists in a team, a diverse level of work styles and expertise were present in this team. Linda's low MSLQ score reflected her pessimism about her knowledge on hydraulics and her skills in building a bike. In the early stage of the project, she once said "I am probably the only one in the group that is not a bike expert, so it is a little harder for me to catch on the things…so it is a slow learning process for me…." However, she took a leader position in data gathering for various presentations and the final report. She took the initiative to play as her role as a person who was responsible in documentation and reporting tasks. Alex, John, and Brian were comfortable with the design process and building the bike. Although they had not had any experience with hydraulics, but for Alex and John, building a bike was just a routine activity. Assembling parts to construct a bike was easy for them.

At the early phase of the project, it seemed to be difficult for this team to select the proper strategy to organize the team. This difficulty might be due to the unfamiliarity of the complexity of the project and the tasks associated with it. However, as the project progressed, individual team members seemed to be able to make necessary teamwork adjustments. In one instance, Brian addressed his concern about the need for his team to document all files in more structured and organized manner in one of his email messages to his teammates. As each member worked on the same task individually, a certain method of file archiving was necessary. Consider portion of his email message below:

> Hello all,
> This should have been done awhile ago, but we need to get some basic organization details out of the way. We need to store ALL of our files in one place, and this should be the ONLY place these files are located. This will be very important as we amass more important files. This way we do not have 5 copies of the different revision levels of the same file floating about. This will mean that you should download the file before you start working on it and re-upload and over write it as soon as you finish working on it. Do not store any files that others will need on your computer always keep them in netfiles. I have seen the hassle that this can save especially when we get to modeling and drawings. …….

In the same email message, Brian had expressed his concern about the team's progress, particularly in preparing a presentation for the team's status report to the advising professor and PHP. In that particular email, Brian had also suggested having a meeting to discuss the preparation of the upcoming team presentation.

In general, each member of the team had individually and collectively monitored the progress of the project. This phenomenon was easily seen in their communication activities. Eighty-seven percent of the email messages exchanged among these four students were evaluative in nature and few of them contained suggestions and instructions. During weekly team meetings, they evaluated their progress on tasks they were currently working on.

<u>Design Process</u>

Like other engineers, these students initiated their working journey by first constructing a design strategy that consisted of six steps. Constructing a design strategy that guides the design process is common, not only among expert engineers, but also among novices like these students, since it is taught in engineering education (Dym & Little, 2000). This six-phase design strategy was constructed and evaluated through analyzing the functional role of their thoughts and feelings about their own thinking activities (Paris & Winograd, 1990), and this strategy was used as a design roadmap that reflected the six major tasks this team had to accomplished.

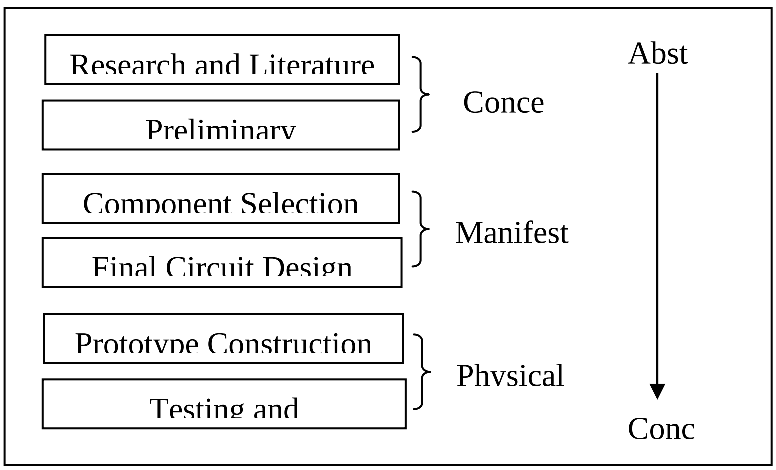

Figure 1. Design-phases and levels of

This team divided their design activities into six major phases reflecting six big and distinct chunks of tasks, as shown in Figure 1. They were: (1) research and literature review, (2) preliminary computational analysis, (3) component selection and evaluation, (4) final circuit design, (5) prototype construction, and (6) testing and modification. This team constructed its design strategy based upon each team-member's understanding of the problem and their strategy to solve it. Building a design strategy (e.g., the six major design phases), which reflected their mental model of both the problem and the solution, are common among engineers. A study conducted by Jonassen, Strobel, and Lee (2006) found that engineers are aware that within ill-structured problems, such as this hydraulic bike design project, there exist of numerous well-structured problems in which they have multiple and often conflicting goals. Because they are generally ill-structured therefore there often exist multiple solution paths that engineers may choose from to solve the problems.

A typical design process model (Dym & Little, 2000) consists of ten steps which includes a set of finer steps such as (1) clarify objectives, (2) establish requirements, (3) identify constrains, (4) establish functions, (5) establish specifications, (6) generate alternatives, (7) analyze design, (8) test and evaluate, (9) refine and optimize, and (10) document design. Although it was possible to identify most of these refined steps in this team’s six-phase design strategy, it was interesting to learn that this team did not explicitly include steps like generating design alternatives and document design in the team’s design strategy. These students argued that their design strategy reflected their approach to produce a working hydraulic bicycle according to their understanding of the problem. Those six steps were logical and they made perfect sense to them. It seems to be apparent that these students had perceived their design project as merely about constructing a physical object. They seemed to view the design project more from the hardware producing aspect than from the engineering design process. It was obvious that this team’s design strategy was a roadmap that was intended to bring the design task from its abstractive state closer to its concrete end object. Each design phase had become the transitioning phase for the next phase and it led this team to focus themselves from their initial abstract and conceptual state of understanding to a more concrete object. The abstract and qualitative understanding of the project had eventually become manifested into real physical components before they were finally able to produce a working hydraulic bicycle.

In order to gain a better understanding of students' self management of cognition during the design processes, each of the design phases will be explored in detail. To simplify the discussion, the prototype construction phase and the testing and modification phase are combined.

Research and literature review. Research and literature review was conducted to help these students better understand hydraulic theory, schematics of past hydraulic bike designs, and the existing patents. In this design phase, these students tried to understand the hydraulic system and its application for a designing a hydraulic bike by decomposing the hydraulic bike into its components and identify the structure, function, and behavior of each component. As Linda put it, "During this phase, we focused on the *what* thing rather than the *how* thing."

During this phase, these students acquired some declarative knowledge about the project by first identifying the components, design parameters, and relationship among those components that might affect the performance of their hydraulic bike. Among others, pumps and motors were considered to be the key components that had a direct impact on the hydraulic system's performance. Each pump type has its own working characteristic that may influence the flow rate and pressure to components downstream. These hydraulic forces were functions of both pressure and area, and this simple relationship between pressure and area gave way to the mechanical advantage associated with hydraulics. Some losses in the system could also be avoided if the right viscosity of fluid was used in the design.

It was interesting to learn that these students also learned historical aspects of the hydraulic bike by evaluating existing patents. They found that each of the patents marked a first in the field of hydraulic bicycles but these designs are not cumulative. This team learned about this discontinuity of earlier hydraulic bike design accomplishments as it was reflected in their final project report: "Many great design features that were innovative in 1980, like the ability to remove the rear wheel without breaking the hydraulic circuit, are not integrated into later designs" (Orange Team and Blue Team, 2005, p. 17). The lessons learn from this design phase were integrated in this team's future design.

The research and literature review were conducted in order to gain a firm grasp on the governing main concepts of hydraulics, bicycles, and previous hydraulic bicycle designs. The team believed that because they had a good understanding of these three concepts, they had a clear idea on the complexity of the design tasks. Moreover, they also believed that by having some understanding of these three main concepts, it had given them some level of self-confidence in completing the project. Understanding these technical issues did not only provide this team with some insights about the technical aspects of building a hydraulic bike, but it also offered a common metacognitive tool (Paris & Winograd, 1990) so these students could achieve self-appraisal and self-management of their own thinking.

Preliminary computational analysis. After having a more qualitative analysis of the project from the previous phase, this team proceeded with a quantitative analysis through numerous computer simulations. This second phase was a phase where these students tried to gain an understanding of the project from the operational side of the hydraulic system. Through this quantitative analysis, these students had a better insight on how efficiency of the hydraulic system could be optimized, which helped them make more engineering sound of decision for components selection.

The quantitative analysis began by first thinking about the bike from the technical aspects and the challenge of the bike competition. The underlying argument of this design project was to have a working and efficient hydraulic bike to win the race. To ensure a high efficiency bike, these students had to consider all the forces that might both promote and inhibit the bike from moving freely forward. These students knew that there were two approaches available for them to model the hydraulic system of the bike. They could view the bike from time-based Newtonian physics or a time independent system. Time dependent energies are non-conservative energies calculated by measuring the time spent between two coordinates. This energy change is very much related to the rider's speed. The direction and the speed of the wind, the course elevation for the race, and the rolling resistance on both bike's front and rear tires are some of the many factors that influence the energies entering and exiting the system. They were independent on time because these energies were a function of position. Time-based Newtonian physics was previously considered to be a reasonable approach to model the system, but later they chose to build a system that centered on Conservation of Energy. The decision was made because the funding organization had given them the spatial coordinate of the race course which provided them with a more real race condition.

Identifying those various forces was the first step to learn the causal relationship between the *input* and *output* of a hydraulic circuit that might influence the bike's performance. They knew that the bike's velocity was dependent upon numerous factors such as the elevation of the race course and speed and direction of the blowing wind. These factors that had to be considered in the design of the hydraulic circuit had surely become complex. To simplify the complexity of the design of the hydraulic circuit for the bike, these students had first built design models that reflected the structures and functions of a hydraulic bike. In this second design phase, the main goal was to produce a hydraulic bike using models that could mimic the end product of a hydraulic bike and analyzed quantitatively.

During this design phase, this team did an analysis on the power system that was used to turn the bike wheels. As far as the power requirement was concerned, the design had evolved twice. In the early stage, they were thinking about a hydraulic bike that solely utilized input energy from the cyclist powering the pedals and the energy gained from going downhill. However, the team later initiated the idea of putting an accumulator to the model, to see whether the use of an accumulator could improve the efficiency of the hydraulic system. After analyzing both models, the team finally decided to go with the model without an accumulator. From this experiment, the team was able to see the correlation between two or more design parameters (e.g., the drive train efficiency affected by the change in weight) in the simulation analyses. For example, the students found that the use of an accumulator did not provide any benefit in the endurance course, since the stored energy was depleted on any steep hill the cyclist would experience.

It was apparent that this team had explored all possible options to improve the hydraulic design and tested them through a series of computer simulations. Although considering alternative designs was not included in the earlier stage of the design process (i.e., during the construction of six-phase design strategy), thinking about alternative designs was incorporated in this phase. The alternatives were considered because of the help of computer analysis. The computer analysis gave these students valuable information that had helped them, select the hydraulic model they wanted to incorporate in their bike, and select appropriate components that could support the model. These computer simulations had indeed brought the design process a step closer to the functionality of a physical hydraulic bike.

Component selection and evaluation. These students argued that their biggest concern in this design phase was getting the highest possible efficiency together with the lightweightness of the hydraulic components and circuit. Each component and the overall hydraulic circuit had to function within the desired operating range. Among many, there were two components that this team concerned the most: the hydraulic components and the bicycle frame. Selecting a bicycle frame was not a major issue for this team, especially for Alex and John, since they both had enough experience in constructing new bikes; however, selecting a right pump for the bike was a big challenge for this team.

At first, there were six different hydraulic pumps available to select. These hydraulic pumps were provided by project funding organization for free and therefore, the students decided to start evaluating these pumps before thinking about getting their own pumps. However, they discovered that these pumps did not match the specification required for their design and therefore, they had to order other types of pumps. There were two reasons why selecting an appropriate pump was not an easy task for this team. First, it was lack of prior knowledge of these hydraulic components. No team members had appropriate knowledge about the main hydraulic components (e.g., hydraulic pump) prior to this project. Therefore, they needed to learn about the components before they were able to select the most suitable components for the design. Second, there was no complete hydraulic system that mocked the actual bike available for the testing. The team needed to build a testing apparatus by first coming up with the testing strategy and then building the testing instrument.

The main goal here was to select the most appropriate hydraulic pump for the bike by first analyzing each of the pumps' performance. A relatively simple analysis was done using an Excel spreadsheet. By using the Excel spreadsheet, the team was able to calculate the efficiency of each of the pumps. Through this analysis, these students learned that each pump had a unique performance characteristic. For example, the team found that the efficiency of the Haldex pump varied with speed while the Marzocchi pump varied with pressure.

Interestingly, the team did not select the suitable pump for the design from these tested pumps. However, the earlier testing activities had given these students an adequate foundation for the range of pumps that were needed for operation. That allowed for them to order pumps and motors that were likely to work in the expected operating range. It was obvious that none of these tested pumps had satisfied the requirements of the team's design. After ordering and getting new pumps, the team applied the same pump efficiency testing procedure. As mentioned in the project final report, the data from these tests were collected and analyzed in the same manner as before, only this time the results were treated slightly differently.

During this testing activity, the team members used their existing knowledge and skills to make their judgments about those pumps. The unexpected had once again occurred. During the testing of the new pumps, the team found that the efficiencies that resulted from the testing were higher than one. They knew that something must have gone wrong. Efficiency could not be more than one. They knew that this error was caused by the inability to use the same dynamometer on a larger apparatus. The calculation process of the pumps' efficiency used a larger DC motor; therefore, it was decided that these calculations would no longer be the efficiencies. Instead, it would be treated as a comparative index. Pumps with higher indexes therefore had higher efficiency.

Final Circuit design. After deciding on the types of components used for the bike, the students had to start designing and building the complete hydraulic system of the bike. They referred to this complete hydraulic system as the *circuit*. Indeed, this circuit was the main part of the bike that transforms the energy of the cyclist to the pressured liquid that eventually moves the rear wheel of the bike.

There were two major activities conducted during this phase: (1) designing and building the supporting parts to connect the selected major components and (2) completing the engineering drawings. These engineering drawings were needed for building the supporting parts and project documentation. They knew that some of these activities could be done simultaneously but some could not.

It was interesting to learn that although the project had almost come to its completion, the team considered working on another alternative model, a chainless hydraulic bike. Brian and Alex took the initiative to start working on this new model while John and Linda continued completing the earlier model. This chain-less model was once brought out into the team's discussion at the very early stage of the design but it was not followed up in the following phases. Perhaps, the team had realized that building a chainless hydraulic bike was much more complex, advanced, and challenging, although it would increase the quality of the design (i.e., improve energy efficiency).

These two sub-groups of students worked in parallel. Branching off into two sub-teams to work on two different tasks was done for the purpose of meeting the project timeline. After having worked on both designs for two weeks, Alex and Brian finally decided to discontinue work on their chainless system and join their other teammates, Linda and John, to complete the existing hydraulic system (i.e., with-chain hydraulic bike system) together. This decision was made because Alex and Brian realized that their design was very complex and they knew that the chain-less hydraulic bike system could not be completed on time. They made a well-reasoned decision to help Linda and Brian complete their original design.

Prototype construction and testing and modification. This phase involved the integration of the parts and testing of the bike. This phase had drastically changed the nature of the project-from its abstract realm into a concrete engineering artifact. For these students, this phase was their moment of truth. They were all eager to see if all of their ideas and work previously discussed and conducted would form a working hydraulic bike.

After putting all the basic components on the bike's frame, everybody focused on the installation of the hydraulic parts (see Figure 2). Lots of effort was put into fitting the pumps together and installing them on the bike frame. The task was to push fluid through the hydraulic motor in which the shaft was connected to the rear hub of the bike. A chain drive was used to power the pump. The hydraulic system was set up to power the pump using a bike crank and chain and allowing the motor-to-rear-wheel unit at the end of the circuit to spin freely. The pump and motor were mounted to a small, sturdy aluminum plate, allowing the gears of the pump and the bike crank to maintain proper alignment.

Figure 2. Transition of the Design Abstraction: From Simulation of the Hydraulic Bike System to Construction

Approaching the end of the project time, Alex and Brian made more changes to the working bike (e.g., moving the fluid pipe to a more appropriate place). They seemed to be unhappy with the bike's appearance, especially with the piping that connected the hydraulic pump to the gear of the rear wheel. More pipe bending and twisting were made to improve the bike's aesthetics. Although aesthetics was one of several other aspects that were evaluated in the senior design project, these two students focused on the aesthetics issue for personal satisfaction.

Discussion

The findings of this study enhance and support pre-existing assumptions on how typical engineering students engage in a team-based project. In regard to these findings, this discussion will focus on two things: (1) the work categories that reflect all mental and physical activities during the project; and (2) the important knowledge to metacognition during the project.

All students' activities can be classified into three work categories: *work of consolidation*, *work of engagement (or doing)*, and *work of appreciation* (see Figure 3). Within each work category, these students might have engaged in a certain degree of planning, evaluating, and regulating activities according to the context of task they encountered. Marzano, et al. (1988) argued that declarative, procedural, and conditional knowledge are important to metacognition. Each work category may require students to apply one, two, or all those three types of knowledge.

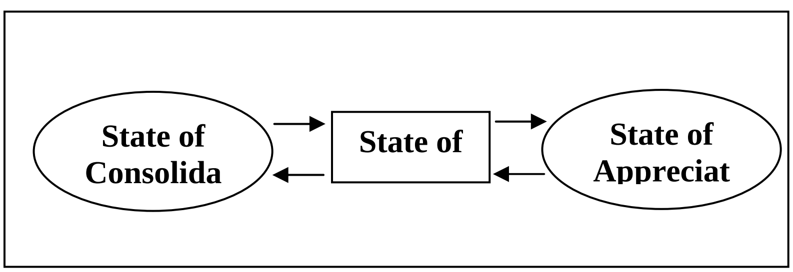

Figure 3. Level of Working State

Work of Consolidation

Students' self-management of cognition had been used in equal intensity throughout these three categories of work state. These three work categories were both the starting and ending points, which means that consolidation, engagement, and appreciation had occurred at any time throughout the progression of the project. As it was a fluid process, often students needed go back and forth between those three work categories. First, these students had to understand the problem, the hydraulic bike, with all the complexity of numerous tasks associated with the problem. Before starting the project, these students assessed their resources. Phase 1 of the design strategy (i.e., research and literature review) and Brian's email message could be considered as the *work of consolidation*. During design phase 1, this team assessed each member's current knowledge and the existing hydraulic bike design and patents. Although most consolidating activities happened more often during design phase 1, it should not that the consolidating process could not happen throughout the design process. Brian's email message that suggested his teammates organize the team's filing could be considered as consolidating activity and this email message was sent a few weeks after the project had been started. During this work of consolidation, students inventoried and recollected all the resources (i.e., persons, knowledge, and skills) they had. These students tried to identify what that they already knew (i.e., *knowing the what* and *knowing the how to*) and identified their teammates' strength and weaknesses as well as other external resources. The experience John and Alex had in building a regular bike, had helped this team to move further with relative success for the project. In contrast, Linda's unconfident feeling working on this project could produce a negative impact on this team's total performance; however, as she received lots of support from her teammates and she had contributed her expertise on other tasks in the project, Linda was able to position herself to be beneficial member of her team. The less-structured team organization might have helped Linda learn about the project and contribute to the team's accomplishments. Furthermore, perhaps having a clear individual role that was agreed by all team members to ensure the success of the project at the early stage was essential during this consolidation period. This work of consolidation was a phase where these students exercised their self-appraisal of cognition and evaluate what they had known and what they had not known such as the existing hydraulic bike design and patents.

Work of Engagement

After successfully identifying all their resources, the students were entering the central part of the project, engaging in the design a process, which is labeled as the *work of engagement*. During this work of engagement, these students engaged in planning activities such as selecting a six-phase design strategy, evaluating activities such as comparing various hydraulic pumps' performance from computer simulations, and regulating activities such as choosing other pumps that met the design requirements.

Work of Appreciation

Once a particular design task was completed, an evaluation process was made and these students were valuing their efforts, work accomplishments, and outcomes. Any necessary revisions on working strategy or design solutions were made during this state. The group valued their thoughts, successes, failures, and experiences from all the labor or non-labor activities throughout the project. This work of appreciation was a phase where the students exercised their self-appraisal and self-management of cognition. During the component selecting phase, the team conducted another test for different pumps using the same testing apparatus and technique. Because of their success in pump testing processes this team decided to use similar testing processes for other hydraulic pumps.

In each work category, it was easy to find declarative, procedural, and conditional knowledge applied throughout the design activities. Declarative knowledge is factual. It is knowledge to answer about *who*, *what*, *when*, and *where*. Procedural knowledge is about knowing the *how* part. Conditional knowledge is about what strategy works, when and why. Marzano et al. (1988) argued that declarative and conditional knowledge are primarily used during the planning processes. When these students were constructing their six-phase design strategy, they knew what they needed to build and how to build the hydraulic bike. In this study, it was found that these students' understanding of the project was heavily focused on the physical design outcome, and not on the detailed process. This finding supports the findings in one of Chi's (1981) studies about the way novices and experts differ in solving problems. She claimed that novices focus on the problem's surface attributes. In this study, it was also found that the team's six-phase design strategy did not include the finer steps or processes that are typically listed in the literature (Dym & Little, 2000).

During evaluation and regulation processes, it was found that these students were exercising all of their declarative, procedural, and conditional knowledge. When Linda was evaluating the fact that work could be accomplished efficiently if somebody who was not involved in a particular task monitored the work progress, she was exercising her understanding that objective monitoring could be established from the outsider. When Brian was suggesting a better filing system to document and access individual member's work progress, he was exercising his declarative (i.e., unorganized filing system was confusing and could yield to accessing invalid data), procedural (i.e., downloading files and then uploading them back in the Netfiles), and conditional (i.e., knowing that this revision should be done at the early stage of the project) knowledge.

As this study was a single instrumental case study (i.e., evaluating metacognition in the Orange Team), the findings are not intended to draw conclusions that are generalizable to other cases of engineering students working in any kind of design task. However, this study has provided a case that reflects a typical work environment that illustrates the use of the metacognitive model introduced by Paris and Winograd (1990).

These students' execution of self-management of cognition, which was manifested in their planning, evaluating, and regulating activities, has given us better understanding of team work dynamics that is often not in line with the intended teaching objectives or with the instructional designer's goal. This study suggests the need for engineering educators to value equally their grading of students' project management skills and students' design skills in producing the intended design object.

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