An In-depth Analysis of Open-ended Biomedical Engineering Design Problems and the Role of Metacognition in Their Solutions

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Introduction

The need to build problem solving skills in STEM undergraduates has been widely reported [1]. In biomedical engineering specifically, the application of problem solving skills to engineering design problems is especially desired. This is due to both the increasing demand from industry as well as the growing expectation that biomedical engineers will continue to play a significant role in the growth and innovation of new biomedical technologies [2]. Significant curricular efforts have been made to strengthen these skills throughout our department's undergraduate experience, which includes both paper-based and prototype-based design activities centered on the engineering design process [3]. The impact of these efforts however on the development and use of problem solving in the context of design, or design thinking skills, has yet to be determined.

When students are faced with solving an open-ended design problem, there may be specific parts of this practice that students either do not understand, do not implement correctly, or do not know to attempt when solving open-ended design problems. Several studies have investigated how first year undergraduate engineering students in particular, approach design problem solving, and their interpretation and knowledge of engineering design [4-7]. These studies used various methods to evaluate students' design thinking including pre- and post-tests associated with group design projects in a classroom setting [4], pre- and post-essay response critiques of two design plans [5], gender differences in students' attempts to evaluate design factors [6], and short essay critiques of a design process displayed by a Gantt chart [7].

Other studies have focused on senior undergraduate engineering students. One such study conducted interviews with eight fourth year students in which they were presented with an open-ended design problem, and evaluated the student recommendations for design specifications and costs [8]. Together, these studies provide insight on the effects of problem solving on undergraduate engineering students, yet little is understood about first year students' abilities to employ an iterative engineering design process on open-ended design problems or the difficulties students have in applying the design process to address a problem statement. It is important that educators recognize where introductory students struggle when implementing the engineering design process and what concepts cause them difficulty in order to better develop problem-solving skills in future engineers.

In this study, we conducted and evaluated interviews with twenty biomedical engineering students in an introductory biomedical engineering class responding to three open-ended design problems to gain insight on design process knowledge and application. The results from this work will highlight specific areas of problem solving and the design process that students struggle with, enabling engineering education researchers and professors to understand how to help introductory students better develop engineering design thinking skills.

Goals

The overall goals of this study are to (1) analyze students' problem-solving work in detail to better understand why and how students have difficulty with problem solving in biomedical engineering design and (2) determine correlations between incoming design knowledge and metacognitive awareness with problem solving success.

Methodology

Design

To gather a baseline of students' design knowledge, the Comprehensive Assessment of Design Engineering Knowledge (CADEK) diagnostic test [9] was administered to students in the first and last week of class (Figure 1). Students were also asked to complete an online Metacognitive Awareness Inventory (MAI) [10] during week 2. In addition to the CADEK and MAI, students answered an open-ended design problem on their first quiz (in Week 5), from which ten high performing and ten low performing students were identified and asked to participate in one hour think-aloud interviews (TAInt). The TAInt were conducted during weeks 7 and 8 of the quarter during which participants were encouraged to speak through their thought processes while solving three open-ended biomedical engineering (BME) design problems.

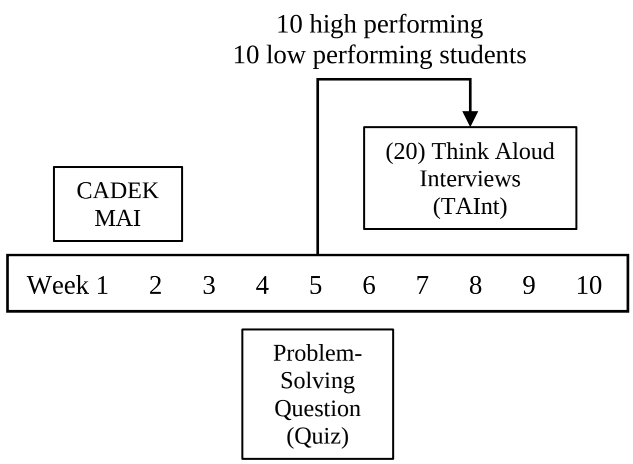

Figure 1. Study design and timeline. The CADEK, MAI, and problem-solving quiz were administered to all students in an introductory BME course. Twenty students were selected based on performance on the quiz and participated in individual think aloud interviews.

Participants were enrolled in a first-year introductory BME course that introduces the field through BME specialization introductory lectures, prospective BME career guest lectures, and team-based hands-on design challenges. This two-unit course consists of one 50-minute lecture and a 3-hour discussion session focused on engineering design each week of a 10-week quarter. There were 142 students enrolled in this introductory course.

Based on scores from the week five quiz, ten low scoring and ten high scoring students were asked to participate in TAInts. Participants received a small stipend for their participation in this Institutional Review Board (IRB) approved study. Study participants were 70% first year, 25% second year, and 5% third year students.

Incoming design knowledge

Students in the introductory BME class completed the CADEK in the first week of class. CADEK is a validated open-ended assessment that measures students' engineering design knowledge. Students were evaluated using their responses to part A of the first CADEK question, which asked them to describe and/or diagram their understanding of the engineering design process.

Metacognitive Awareness

The MAI, or Metacognitive Awareness Inventory [10], was administered at the start of the course and assessed students' metacognition based on their responses to 52 true/false statements. Participants indicated if they identified with the given statements based on their past behaviors. In answering the questions, students did not know which statements corresponded to which categories of metacognition. The categories assessed on the MAI include knowledge of cognition and regulation of cognition. Knowledge of cognition is further broken down into the following subcategories: declarative knowledge, procedural knowledge, and conditional knowledge. Similarly, regulation of cognition is subcategorized into: planning, information management strategies, comprehension monitoring, debugging strategies, and evaluation. The results of the MAI were used to determine if any correlations exist between the discussed factors and resulting subcategories with problem solving success in open-ended design problems.

Think Aloud Interviews

Think aloud interviews (TAInt) were conducted during weeks seven and eight to better understand how students think through an open-ended engineering design problem. Before beginning the interview process, the interviewer asked students if they were comfortable with visual recording of their papers and auditory recording of their voices. All participants signed a consent form before beginning the TAInt. Participants were encouraged to ask questions throughout the interviews, but were advised that many could not be answered. Questions concerning vocabulary were allowable, but any associated with the design process, user needs, design limitations were not answered. The interviewer also emphasized the importance of students speaking through their thought processes.

The interviews were composed of three distinct open-ended engineering design problems in which students were asked to read a problem statement and provide a potential design solution while showing and describing all work and considerations. Each problem contained a different degree of technical terminology with problem 1 having the least and problem 3 containing the highest level of technical terms. Each participant was given twenty minutes per question to describe a solution to the problem statement. Students were not aware of a time limit until prompted to begin the following question if time ran out. If participants were quiet for extended periods of time, the interviewer asked if they were thinking or reading and reminded them to think aloud. During most TAInts, the interviewer interjected to ask questions if the interviewees' design intentions were unclear. In doing this, the interviewer gained better data on participant perceptions concerning why or how their design solutions functioned.

Data Analysis

The COSINE (Coding System for Investigating Sub problems and the Network) method [11] was utilized to analyze students' difficulties during the problem-solving process. In COSINE analysis, sub problems correlating with specific steps of the engineering design process were assigned a code based on student performance on a particular task (Table 1). In this study, the original COSINE codes, which were developed for chemical stoichiometry problems, were modified to include only four codes that were relevant for open-ended engineering design solutions. In assigning these codes, students' difficulties and successes, or knowledge structure, are quantitatively represented for further analysis. Refer to Table 2 for code details and to Figure 2 for the modified coding scheme.

Table 1. Sub problems that correlated with each step of the engineering design process were used to determine participant performance on a particular problem solving task.

Sub Problems	Engineering Design Process Step
A	Identify Problem
B	Acknowledge Current Solutions
C	Acknowledge Current Solutions' Limitations
D	Identify User Needs
E	Address User Needs in Final Design
F	Formulate Engineering Metrics to Correlate to Defined User Needs
G	Address Engineering Metrics in Final Design

Table 2. COSINE codes were determined for each sub problem (Table 1) to describe participant performance on each of the three problems presented during the think aloud interview.

Codes	Meaning	Explanation
S	Successful	Students identified all components of a successful solution to a design step.
UDI	Unsuccessful - Did Incorrectly	Students were assigned this code when they attempted a design step, but were unsuccessful in its completion.
DD	Did Not Know to Do	Students were unaware of a necessary design step and did not attempt to address it.
URH	Unsuccessful - Received Hint	Students were given a hint after being unable to identify the main problem in the provided statement. They also had to successfully use their hint to determine the problem.

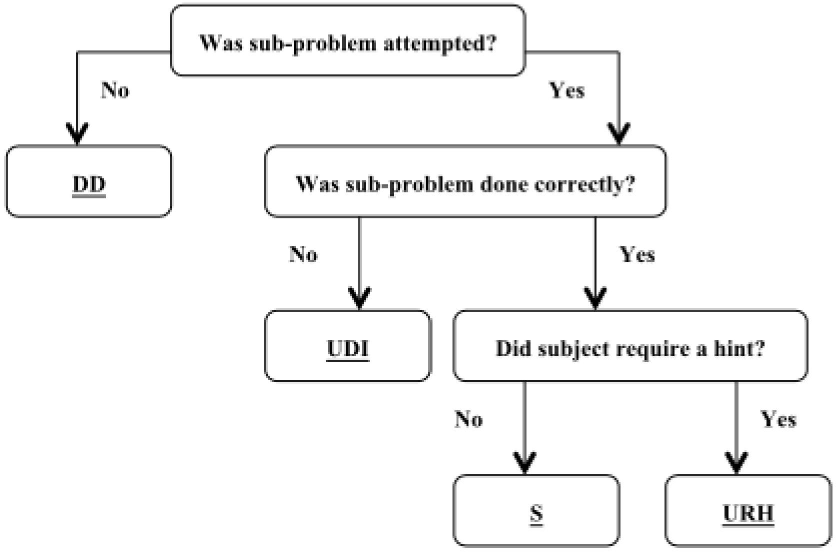

Figure 2. Coding scheme utilized to assign COSINE code (listed in Table 2) for each sub problem.

Two quantitative metrics to describe the success rates of participants on a specific sub problem are the complete success rate (CSR) and attempted success rate (ASR). CSR is the number of assigned S codes divided by the number of all assigned codes. ASR is the number of S codes divided by the sum of all codes except DD. In other words, CSR represents the complete success rate whether the sub problem was or was not attempted while ASR expresses the complete success rate of attempted sub problems. In using these metrics, a representation of participants' complete success rates on specific design steps can be identified.

Another way to describe participants' outcomes is to evaluate each design step's degree of success. For example, while a participant might have identified three out of four user needs, the user need identification design step (sub problem D) would be considered incorrect in determining CSR and ASR since all four needs were not addressed. In recognizing this, calculations based on correct percentage were also determined for every design step. A calculation of this kind for a student who identified three out of four needs would result in 75% degree of success for that specific design step.

Additional analyses were performed to assess correlation between incoming design knowledge and metacognition on problem solving performance. The Pearson Product-Moment Correlation Coefficient was calculated and used to determine statistical significance ($p<0.05$).

Results and Discussion

All participants attempted to generate a solution for each of the three problem statements. The process students used to achieve these solutions however, varied in degree of alignment with the steps of the engineering design process, as indicated in Table 3. Overall, while 70% of participants successfully identified the problem (sub problem A) for all three problem statements, only 17% and 2% identified all specific user needs and formulated all engineering metrics, respectively. It is important to note that sub problems E and G include incorporation of only those user needs (sub problem D) and metrics (sub problem F) identified by the student. Therefore, of those students who attempted to formulate engineering metrics (sub problem F), 96% incorporated their metrics in the proposed design solution (sub problem G). Both attempt success rate (ASR) and complete success rate (CSR) are metrics that measure total success in each sub problem. Total success for each sub problem was determined using generated rubrics where all possible responses for each sub problem were recorded. Possible responses were those that could be determined by the written problem statement alone, and ensured that level of prior knowledge or possible inferences would not impact level of success. Sub problem F, formulating engineering metrics to correlate to defined user needs, was only successful for one participant in one of the three problems.

Table 3. Overall Attempt Success Rate (ASR) and Complete Success Rate (CSR). ASR and CSR were calculated for each sub problem across the three problem statements for each participant.

Sub Problems	ASR (%)	CSR (%)
A. Identify Problem	70	70
B. Acknowledge Current Solutions	65	55
C. Acknowledge Current Solutions' Limitations	61	55
D. Identify User Needs	17	17
E. Address User Needs in Final Design	73	72
F. Formulate Engineering Metrics to Correlate to Defined User Needs	3	2
G. Address Engineering Metrics in Final Design	96	43

This reflects in part, the level of incoming engineering design process knowledge, as measured by the CADEK taken during the first week of the course. The first question on this inventory asked students to “describe and/or diagram your understanding of the engineering design process.” As shown in Table 4, 90% of participants mentioned the importance of brainstorming and/or selecting an idea, 70% mentioned the need for testing to make sure needs are met, or verification, and 65% described prototyping as an essential part of the process. Solution criteria that correspond to the study sub problems were included for comparison purposes. Only one participant however, addressed the need to formulate engineering metrics in this question, consistent with the calculated success rates for sub problem F in Table 3.

Table 4. Incoming design process knowledge of study participants. Success rate is defined as percent of study participants that mentioned corresponding listed solution criteria in their response to question one on the CADEK.

Solution Criteria (Sub Problem)	Success Rate (%)
Identify Problem (A)	50
Acknowledge Current Solutions (B)	10
Acknowledge Current Solutions' Limitations (C)	5
Identify User Needs (D)	20
Address User Needs in Final Design (E)	0
Formulate Engineering Metrics to Correlate to Defined User Needs (F)	5

Address Engineering Metrics in Final Design (G)	0
Brainstorm and Idea Selection	90
Prototype	65
Verification	70
Validation	5
Review	50
Final product	35

While the computed complete success rates, ASR and CSR, are one indicator of a students' ability to apply the engineering design process when approached with an open-ended design problem, arguably, it is the *degree of success* that informs us of whether a student completely overlooked a sub problem versus overlooked specific components of a sub problem (Figure 3). To illustrate this, sub problem D yielded an ASR and CSR of 17%, stating that participants identified all user needs in 17% of all problems across all the participants. In contrary, measures of degree of success for sub problem D, which identifies percentage of user needs that participants identified for each problem, is significantly higher at 60%, 74%, and 83% for Problems 1, 2, and 3 respectively. Interestingly, while degree of success for user need identification is promising, the ability to generate quantitative engineering metrics that correspond with user needs (sub problem F) remains the sub problem that students failed to communicate most in our study. The degree of success for sub problem F is 22%, 41% and 6% for Problems 1, 2, and 3 respectively. The varying degrees of success are reflective of the nature of the given problem statements' varying levels of technical terminology (i.e. Problem 1 had lowest level and Problem 3 had highest level of technical terminology).

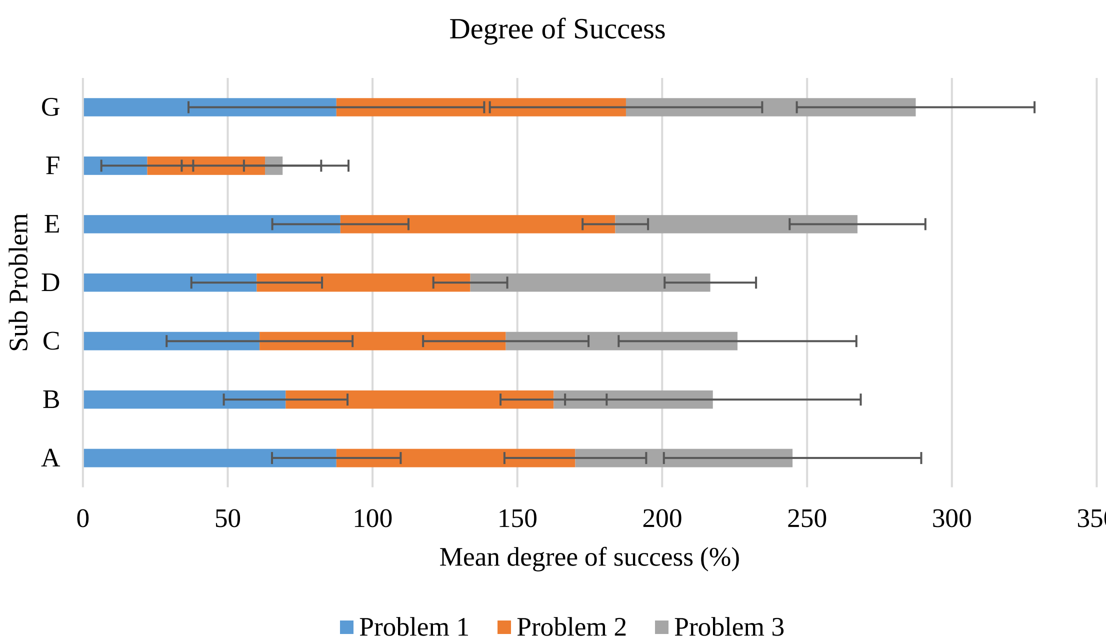

Figure 3. Mean degree of success for each sub problem across all three problems was calculated to determine the extent at which participants achieved a correct solution.

Impact of incoming metacognitive awareness on problem solving

To investigate whether level of incoming metacognitive awareness correlates to degree of success for each sub problem, students were asked to complete the MAI during the first week of the quarter. Level of metacognitive awareness, as measured by both the knowledge about cognition and regulation of cognition factors, for study participants is shown in Figure 4. Participants exhibited highest levels in debugging strategies, or strategies to correct comprehension and performance errors. This was measured by responses to statements such as, “I re-evaluate my assumptions when I get confused” and “I stop and reread when I get confused” on the MAI. Participants also exhibited higher levels in conditional knowledge, which computed scores from responses to statements such as, “I learn best when I know something about the topic” and “I use different learning strategies depending on the situation.” Participants scored lower levels in the areas of planning, which can be described by a student’s ability to plan, goal set, and allocate resources prior to learning, and evaluation, which describes students’ ability to analyze performance and effectiveness of a strategy after a learning episode.

While there were no significant levels of correlation between level of incoming metacognitive awareness and overall problem-solving success rate, the ability to address user needs in final design (sub problem E) for Problem 3 specifically, did have a positive correlation ($r=0.768$) with reported Debugging Strategies. Since problem 3 had the highest level of technical terminology it may have required participants to utilize debugging strategies to propose a solution.

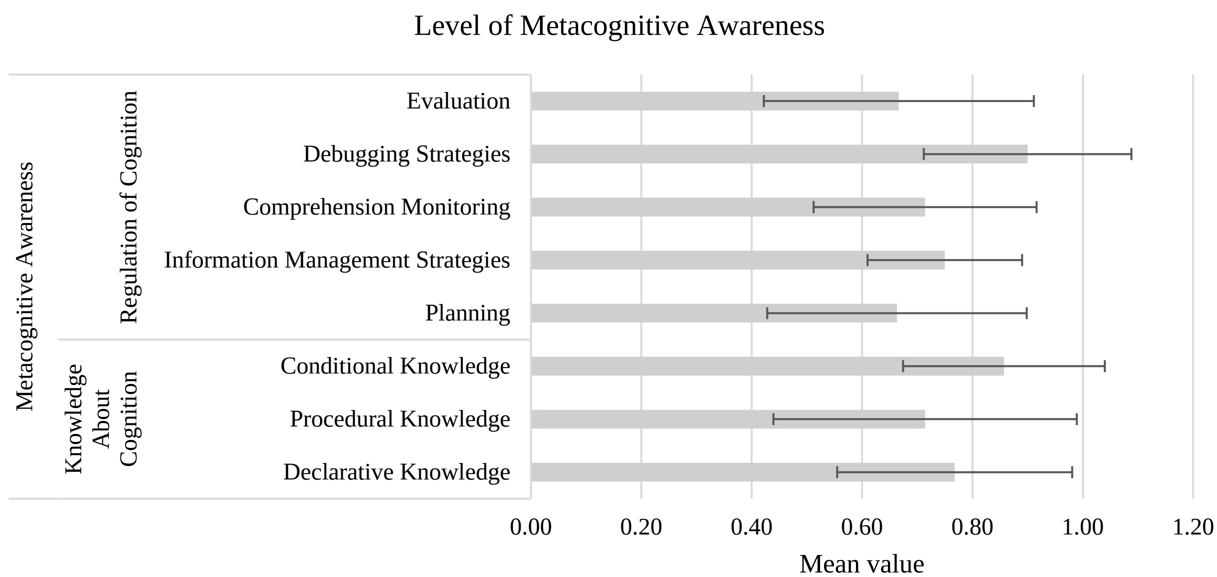

Figure 4. Metacognitive awareness inventory (MAI) results. Knowledge about cognition and regulation of cognition factors were calculated using self-reported responses to the MAI.

Impact of incoming design knowledge on problem solving

Performance on the first part of the CADEK was compared to participants’ overall problem-solving success, as well as to performance on each individual question. The only statistically significant comparison that resulted was a negative correlation ($r = -0.545$) with the ability to formulate engineering metrics (sub problem F) on problem 1. Therefore, when asked to describe the engineering design process, those students with lower scores had higher success scores with respect to generating engineering metrics for the first of three open-ended problems used in the study. This suggests that when students are asked to come up with a design solution for a problem statement that is easier to understand, they are more likely able to generate quantitative metrics to define their potential solution than with problems of greater technical terminology. Students may be faced with a cognitive overload in problems that contain greater technical terminology, as their working memory capacity is easily reached. As a result, they may be unable to process all components/sub problems that are required to achieve a successful solution. As shown in Figure 5, though not statistically significant, there is higher correlation between score on CADEK and ability to generate quantitative metrics for problem 3, the most technically challenging question. Interestingly, this trend is observed for sub problems C-G as well.

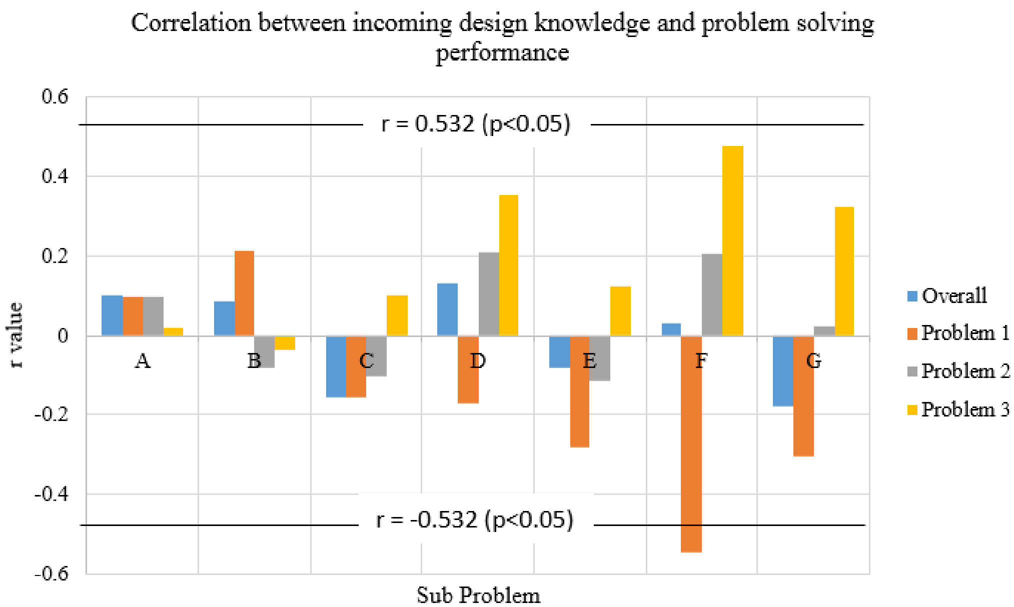

Figure 5. Correlation between incoming design knowledge and problem-solving performance. The Pearson Product-Moment Correlation Coefficient was calculated and used to determine statistical significance ($p<0.05$).

Problem solving strategies

Based on degree of success (Figure 3) for all sub problems, the top five high performing and low performing participants were identified. High performing participants scored highest average degrees of success across all sub problems, whereas low performing participants were those that scored the lowest average degrees of success among all participants. Specific problem-solving strategies and behaviors were identified and compared for these selected participants. The use of ranking, re-reading, and drawing as tools for problem solving were identified and compared. As shown in Figure 6, high performing students re-read their problems and used drawings as tools for problem solving more frequently than low performing students, while the low performing students tended to use ranking as a tool more frequently than high performing students. The total usages of these techniques for all study participants are also shown for reference in Figure 6.

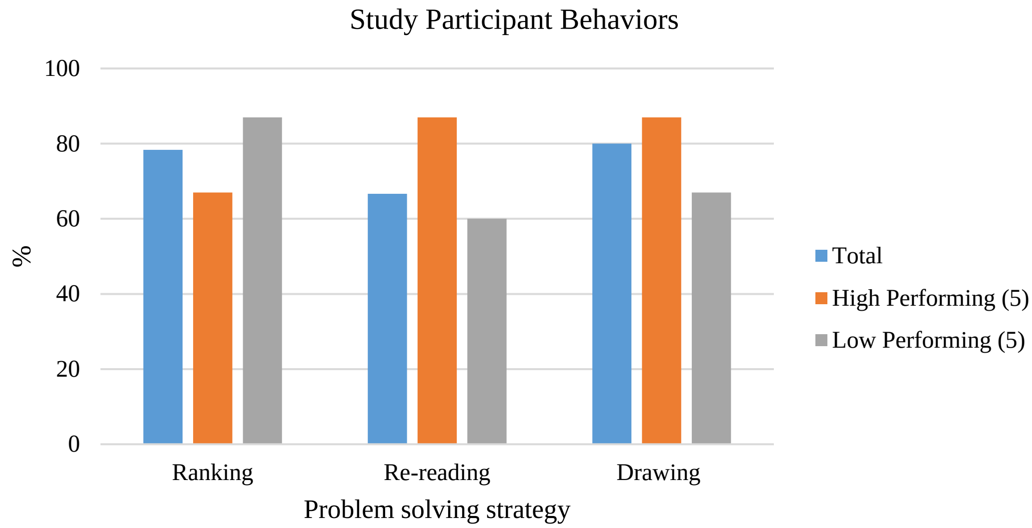

Figure 6. Study participant behaviors were identified and specific problem solving strategies (ranking, re-reading, and drawing) were used to compare participants that had the highest degrees of success (high performing) with those that had the lowest degrees of success (low performing), as determined by the analysis of think aloud interviews (Figure 3).

Implications and Conclusions

When participants were asked to describe the engineering design process, most students emphasized the importance of identifying the problem and subsequently brainstorming solutions to meet the identified needs. Following ideation and selection, testing and review of prototypes were valued aspects of the process. Interestingly, when participants were asked to provide a design solution to a specific problem statement, which included some background information, students not only emphasized the importance of problem identification and ideation, but acknowledged limitations of current solutions to the problem as well as specific user needs that needed to be satisfied. Once user needs were identified, 85-95% of participants integrated these needs into their proposed design solutions. While the translation of user needs into potential design solutions is valuable, the assignment or identification of specific quantifiable metrics for each need was not pursued by most participants. This may be in part due to not having the technical knowledge yet to translate certain user needs into engineering metrics, but as evidenced in their incoming design knowledge test, students may not yet see the value and/or necessity of this important step in the design process. Ultimately, this may be reflective of a misconception of *how* user needs can be most effectively integrated into a design solution. Ideation and brainstorming often are used as open-ended, creative thinking tools to stimulate a wide range of ideas. However, if it were used in conjunction with a systematic process of ranked user needs and quantifiable metrics, generated ideas would be sure to address, at least in part, the end user needs.

The students who performed highest with regards to proposing solutions to open-ended design problems, tended to re-read and draw as they thought through each problem, which may have contributed to their success. Paying close attention to detail, and externalizing their thoughts through drawings may have contributed to their ability to translate the original problem statement into a meaningful engineering design solution. Further studies to investigate how significant these behaviors are to problem solving methodology and success would provide additional insight into how best to instruct and encourage students to actively engage in the problem-solving process.

The results of this study has provided insight into what students think the engineering design process is coming into an introductory BME course, and what process they use when approached with solving an open-ended engineering design problem. As many programs integrate hands-on design projects early in the undergraduate curriculum, this study points to the importance of emphasizing and demonstrating how identified user needs can be translated into quantifiable engineering metrics. Contributions to level of metacognition were minimal, however the ability to "debug" during the design process may be of importance. Certainly, follow up studies to further investigate the role of various metacognitive perspectives are warranted. Assessing students over the course of the BME undergraduate curriculum will also provide insight into strengths and areas for improvement of design instruction across the curriculum.

References

[1] A.R. Saavedra, J.E. Saavedra, "Do colleges cultivate critical thinking, problem solving, writing and interpersonal skills?" *Economics of Education Review*, vol. 30, no. 6, pp.1516-1526, 2011.

[2] A.L. Lerner, B.H. Kenknight, A. Rosenthal, et al. "Design in BME: Challenges, Issues, and Opportunities," *Ann Biomed Eng*, vol. 34, no. 2, pp. 200-208, 2006.

[3] J.H. Choi, "Work in Progress: The Incorporation of Hands-on, team-based design challenges in a large enrollment introductory biomedical engineering course," in *2016 ASEE Annual Conference & Exposition*, New Orleans, LA, 2016.

[4] A. Saterbak and T. Volz, "Assessing Knowledge and Application of the Design Process", in *2014 ASEE Annual Conference & Exposition*, Indianapolis, Indiana, 2014.

[5] R. Bailey and Z. Szabo, "Assessing Engineering Design Process Knowledge", *The International Journal of Engineering Education*, vol. 22, no. 3, pp. 508-518, 2006.

[6] D. Kilgore, C. Atman, K. Yasuhara, T. Barker and A. Morozov, "Considering Context: A Study of First-Year Engineering Students", *Journal of Engineering Education*, vol. 96, no. 4, pp. 321-334, 2007.

[7] A. Saterbak and T. Volz, "Assessing Design Capabilities Following a Client-Based Freshman Design Course", in *4th First Year Engineering Experience Conference*, Pittsburgh, PA, 2012.

[8] E. Douglas, M. Koro-Ljungberg, Z. Malcolm, N. McNeill, T. David and C. Lee, "Moving Beyond Formulas and Fixations: Exploring Approaches to Solving Open-Ended Engineering Problems", in *2011 ASEE Annual Conference & Exposition*, Vancouver, BC, 2011.

[9] G. Okudan, S. Gupta, "Assessment of Learning and its Retention in the Engineering Design Classroom Part A: Instrument Development", in *2007 ASEE Annual Conference & Exposition,* Honolulu, HI, 2007.

[10] G. Schraw, R.S. Dennison, "Assessing metacognitive awareness", *Contemporary Educational Psychology*, vol. 19, pp. 460-475, 1994.

[11] O. Gulacar, T.L. Overton, C.R. Bowman, H. Fynewever, "A novel code system for revealing sources of students' difficulties with stoichiometry", *Chemical Education Research and Practice*, vol. 14, no. 4, pp. 507-515, 2013.