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A Comparison of Design Self-Efficacy of Mechanical Engineering Freshmen, Sophomores, and Seniors

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Abstract

Self-efficacy, a person's belief about their own ability for a particular skill, has been shown to be highly correlated with an individual's accomplishment level. With high self-efficacy, a student will use more cognitive and metacognitive strategies and be more likely to select challenging tasks due to their self-confidence. Upon encountering a problem, an individual with higher self-efficacy is often willing to put in additional effort and is more persistent in solving the problem. The continued effort, persistence, and perseverance will increase the likelihood that the student will be successful in accomplishing their task.

Many reports have indicated that more engineers with strong design skills are needed. Self-efficacy is important because it is a large influence on career choice. If the engineering curriculum effectively develops good design engineers, then the design self-efficacies of the students are expected to be high. As the students take additional courses, their beliefs in their abilities to complete engineering design tasks should increase. The design self-efficacy of engineers is hypothesized to be correlated to ideation effectiveness since self-efficacy and accomplishment level are related.

The study presented in this paper consisted of freshmen, sophomore, and senior students in the mechanical engineering department at Texas A&M University evaluating themselves with Carberry et al.'s Design Self-Efficacy Instrument and participating in a design activity. The concepts generated in the activity were rated for ideation effectiveness using the metrics of quantity of non-redundant ideas, quality, novelty, and variety of the solutions. Results indicated that the task-specific self-concept scores of self-efficacy, motivation, and outcome expectancy did not change significantly as students progressed through the engineering curriculum, although the level of anxiety was less for the seniors than the sophomores. It was also found that the task-specific self-concept scores were not accurate predictors of the design ideation abilities of the students.

Introduction

Self-efficacy is defined as an individual's belief in his or her own capabilities to perform activities in order to successfully achieve a specific outcome. A student with high self-efficacy tends to expend more effort towards the activity, persevere when encountering obstacles, and show persistence in order to attain higher achievements[1]. Additional education can help to improve self-efficacy towards certain subjects, and it has been shown that the amount of engineering experience is highly related to engineering design self-efficacy[2].

In this paper, we are interested in how engineering design self-efficacy changes for students as they progress through the undergraduate mechanical engineering curriculum. This paper describes a controlled experiment conducted with freshman, sophomore, and senior students at Texas A&M University to examine the self-efficacy, motivation, outcome expectancy, and anxiety of the students towards engineering design. Students learn the basics of mechanical engineering throughout the first three years of the undergraduate program and then take courses in their senior year that integrate the basics into design. Each year, the students acquire additional skills to prepare them for engineering design so their design self-efficacy should continually increase.

Since self-efficacy is highly related to academic ability[1, 3-7], we were interested in how engineering design self-efficacy and three other task-specific self-concepts are correlated to design ability and concept generation. A concept generation period is an initial stage of engineering design where designers begin exploring a problem's solution space and develop potential solutions. For the experiment, the mechanical engineering undergraduate students completed a self-efficacy survey and then took part in a design activity. The students were given a design problem and a certain amount of time to generate as many high quality solutions as possible, while aiming for a great variety of novel solutions. The results were evaluated using the four ideation metrics of quantity, quality, novelty, and variety. This allowed us to compare the task-specific self-concepts and ideation metrics to determine the relationship between self-efficacy and design ability.

Background Information

A person's self-efficacy can affect his or her work by influencing the type of work chosen and the effort expended. A specific type of self-efficacy can be increased by learning additional material concerning the specific goals and being motivated towards success[8]. Higher self-efficacy leads to higher achievement behaviors.

Self-efficacy assessments are difficult to create because they need to have a precise measurement consistent with the criteria tasks in order to maximize the influence of self-efficacy as a predictive power[1]. Validation of an instrument is important because it is used as a justification of the adequacy of the measured values[9, 10]. Carberry et al. developed a self-efficacy instrument to study people's self-efficacy towards engineering design tasks and proved three sources of validity: content, criterion-related, and construct[2].

Carberry's instrument examines four task-specific self-concepts, which are defined as "any variables concerning the understanding an individual has of him or herself for a given task"[2]. The four task-specific self-concepts in the survey are self-efficacy, motivation, expectancy of success, and anxiety towards the task. One with high self-efficacy would be confident in their abilities to complete the task, highly motivated, expectant of success, and have low levels of anxiety[11]. The task-specific self-concepts were confirmed to be related and act as an influence on one's self-efficacy[2].

The self-efficacy instrument's design tasks were based on the engineering design process proposed by the Massachusetts Department of Education[12]. It contains eight steps, which form an iterative process that can be found in Figure 1. For each task-specific self-concept, a nine-item scale was developed using the design process. The first item asked for the participant's self-percept towards conducting engineering design as a whole (giving the engineering design score) while the other eight items reflected each step of the engineering design process (averaged to be the engineering design process score)[2].

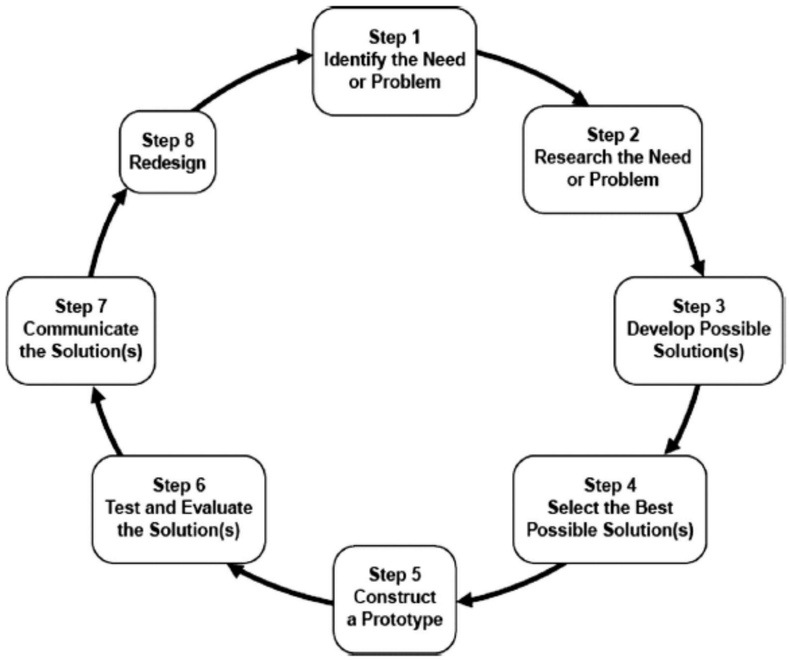

Figure 1. Steps of the engineering design process[12].

Self-efficacy affects a person's behavior towards an activity, and their self-percepts can affect the thought patterns and neurophysiological reactions[13]. Those with high self-efficacy will persevere even in the face of failures because of their beliefs in themselves[14]. Self-efficacy is also an accurate predictor of an individual's ability to successfully achieve his or her goals. Studies have shown that students' views of their capabilities to solve mathematical problems are predictive of their actual performance[7, 15, 16]. In fact, it was found that the math self-efficacy of a student has a greater effect on problem solving than prior experience or perceived usefulness[7]. Collins completed an experiment with students with varying levels of mathematic ability and self-efficacy and discovered that the high self-efficacy children completed and reworked more math problems correctly, regardless of their ability level[17]. This effect of self-efficacy carries over to other fields, and Multon et al. computed that approximately 14% of variance in academic performance was due to self-efficacy during his meta-analysis of 36 studies[6]. It was also found that self-efficacy of scientific-technical tasks is linked to academic performance, persistence, and interest of students majoring in engineering and science[3, 4, 8, 18].

Most students are overconfident in their academic abilities[7, 16, 19]. Since an increase in self-efficacy often leads to additional effort and persistence, the slight overestimation of ability can actually aid an individual in accomplishing their goals[20]. However, too much overconfidence can lead to poor performance because the student may feel that he or she can exert less mental effort to accomplish an academic task[21].

Hypotheses

1. The undergraduate students' engineering design self-efficacy will increase along with their motivation and expectancy of success as the students progress through the mechanical

engineering curriculum and gain additional engineering experience. The degree of anxiety with regard to engineering design tasks will decrease.
2. The participants' task-specific engineering design self-concept scores are directly correlated with the participants' concept generation ability. As the self-efficacy, motivation, and outcome expectancy scores increase and the anxiety decreases, the quantity of non-redundant ideas, quality, novelty, and variety of the solutions will also increase.

Methods

A between-subject experiment was run with students from the freshman, sophomore, and senior classes at the end of a semester to learn about their design self-efficacy and concept generation abilities. The freshmen and sophomore data were taken at the end of the Spring semester in 2012, while the senior data was taken in October and November of 2011 during their final undergraduate semester.

Upon the start of the experiment, students were given a consent form and the Engineering Design Self-Efficacy Instrument. The self-efficacy instrument asks for the participants' degree of confidence in their abilities, their motivation level, their outcome expectancy, and their degree of anxiety for engineering design as a whole and for the eight steps of the engineering design process. For each of the task-specific self-concepts, the nine design process items were scored using a 100-point scale.

After filling out the Engineering Design Self-Efficacy Instrument, the participants were given a packet containing a design problem and customer needs along with blank paper for sketching solutions. The students were also surveyed to determine if they had seen or heard about the design problem prior to the experiment, to which all the students confirmed that they had not. The freshmen and seniors received a prompt to design a device to quickly shell peanuts, while the sophomores designed devices to quickly remove the husk and silk from an ear of corn. The two problem statements are reproduced in Appendices A and B. The freshmen and sophomores generated solutions to their problem statement for fifty minutes, while the seniors were given two hours.

The students were asked to generate as many solutions as possible and to maximize the quality and variety of their solutions. They spent the full time period generating solutions and were notified when there was five minutes remaining. The solutions were analyzed using the ideation metrics: quantity of non-redundant ideas, quality, novelty, and variety, which are detailed in the next section. Regression analyses were completed to compare these metrics to the self-concepts from the self-efficacy instrument.

Of the data collected, analysis was done for 20 freshmen, 20 sophomores, and 22 seniors. The freshman and sophomore data analyzed were randomly selected from the total pool of participants. All of the senior data was analyzed. A minimum of 20 participants per group were chosen in order to ensure that the ANOVAs would be robust even if the assumptions of ANOVA were not fulfilled. Three of the freshmen, three of the sophomores, and two of the seniors were female.

Ideation Effectiveness Measurements

The solutions developed by the students were analyzed using four metrics to quantitatively study ideation effectiveness. The metrics were based on those originally developed by Shah et al.[22] and further refined by Linsey et al.[23]. All of the analyses began on the solution-level. A solution is a full concept developed by a participant. A participant often generated multiple solutions during an idea generation session.

1. Quantity of Non-Redundant Ideas

An idea is a component of the design that satisfies a term of the Functional Basis[24]. To analyze the data, the ideas were listed for each of the solutions and then aggregated for each participant. After removing the redundant ideas, the resulting number of ideas gave the quantity score for a participant. An independent mechanical engineering design doctoral student analyzed at least half of the data for each class. The minimum inter-rater agreement of the three classes was 0.83 (Pearson's correlation), which demonstrates that the metric is reliable.

2. Solution Quality

The participants' solutions were analyzed for quality using a three-point scale, based on the quality metric developed by Linsey et al[23]. A solution received a score of 0 if the technology needed does not exist or if the solution does not solve the given problem. A solution received a score of 1 if the solution is feasible, but only fulfilled some of the designated customer needs. If the solution developed is technically feasible and fulfilled most of the given customer needs, then the solution received a score of 2. Each solution was rated independently and the quality scores were averaged for each participant. Cohen's kappa was used to check inter-rater reliability because a three-point scale was used. The minimum Cohen's kappa of the three groups was 0.42, which shows a moderate agreement according to Landis and Koch[25].

3. Novelty

Novelty is the unexpectedness of a solution when compared to the other solutions[22]. To determine the novelty scores, a bin sort was completed. A bin is a category of solutions with similar features or attributes. The bin lists used were developed for each problem prior to the analysis using different data sets. There were a total of 45 bins for the peanut sheller problem (such as cylindrical rollers, presses, or blades) and 37 bins for the corn husker problem (such as chemicals, adhesives, or abrasives). The participants' solutions were sorted into the bins with the most similar attributes. The novelty scores were calculated for each bin using the equation:

$$Novelty = 1 - \frac{Number\ of\ solutions\ in\ a\ bin}{Total\ number\ of\ solutions}$$

A highly novel bin had very few solutions, leading to a high novelty score. To determine a participant's novelty, the novelty scores of their solutions' bins were averaged. The minimum inter-rater agreement was a 0.75 Pearson's correlation.

4. Variety

A participant's variety score is a measure of the extent of the solution space explored by the participant. It made use of the same bin sort and was calculated by:

$$Variety = \frac{Number\ of\ bins\ the\ subject\ used}{Total\ number\ of\ bins}$$

Participants that explored more of the solution space would use a greater number of bins, thus leading to a higher variety score. A minimum Pearson's correlation of 0.92 of the three groups was found, indicating high reliability.

Results and Discussion

1. Task-Specific Self-Concept Scores by Class

The engineering design (ED) scores and the engineering design process (EDP) scores were found for the four task-specific self-concepts of self-efficacy, motivation, expectation of success, and anxiety. The ED score is how the participant rated the task-specific self-concepts for engineering design as a whole. The EDP score is the average of a participant's ratings for the eight steps of the engineering design process. Both the ED and EDP are scored for each task-specific self-concept. The main difference between the two scores was that the EDP score forced the students to consider each step of the engineering process. Carberry et al. found that the ED and EDP scores were consistent, showing that the task-specific self-concepts were scored similarly whether the participants considered engineering design as a whole or they scored individual steps in the design process[2].

The bar graphs in Figure 2 and Figure 3 show that the ED scores and the EDP scores display similar trends, as expected. There are similarly high levels of self-efficacy, motivation, and expectation, although the sophomores have a slight decrease in self-efficacy and a slight increase in motivation. The level of anxiety is lowest for seniors and highest for sophomores. The Pearson correlation coefficient is 0.80 for self-efficacy, 0.82 for motivation, 0.85 for expectation of success, and 0.87 for anxiety. Since the two scores are consistent, only one was used for further analysis. The EDP scores were chosen because it's scoring should be more thorough since the students examined each step of the engineering design process.

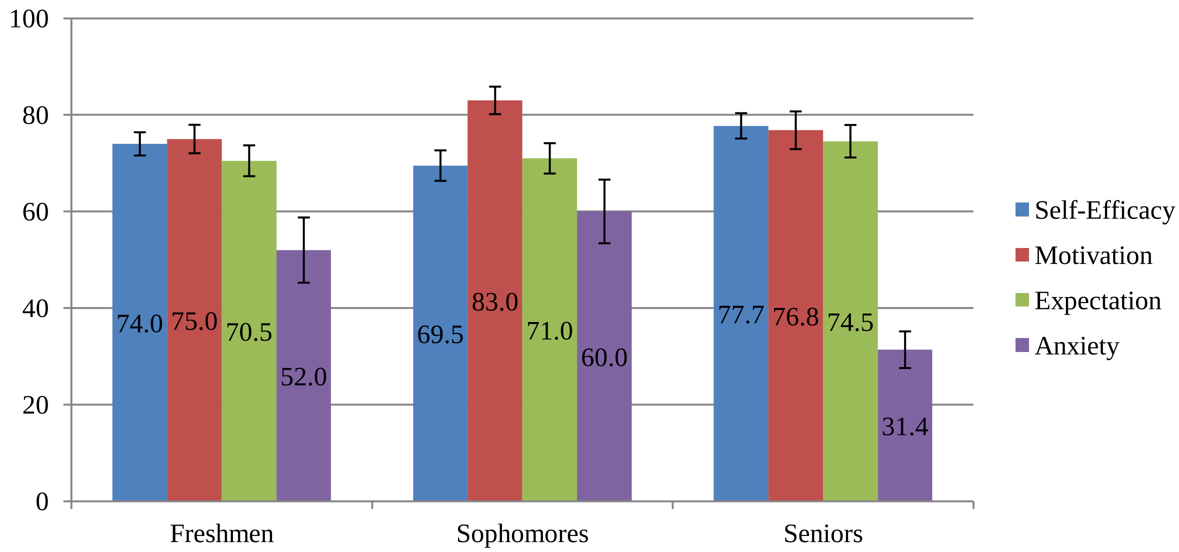

Figure 2. Mean engineering design (ED) task-specific self-concept scores for freshmen, sophomores, and seniors. Error bars show ±1 standard error.

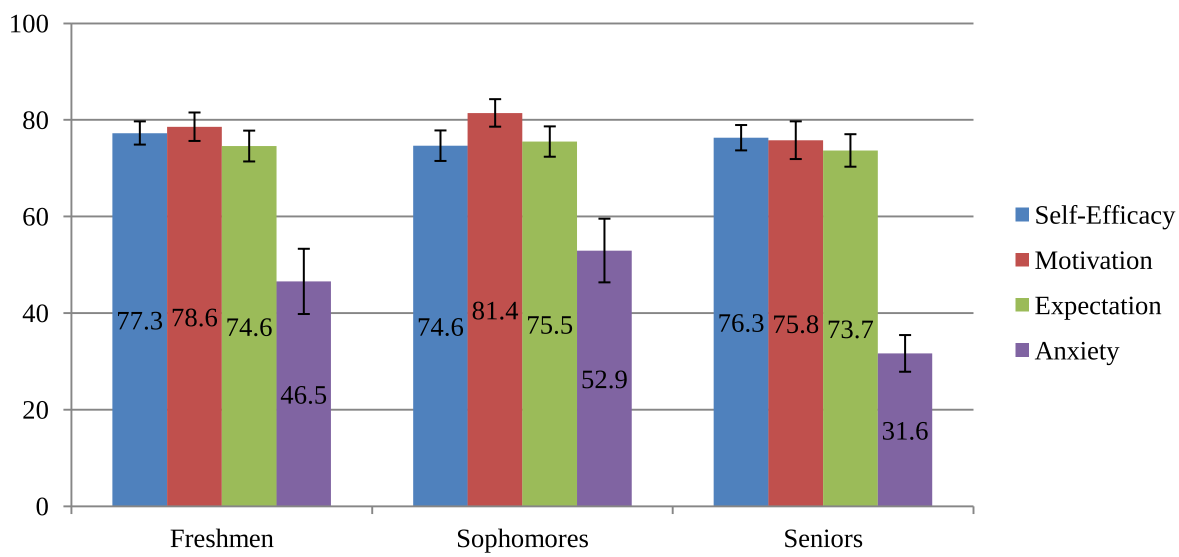

Figure 3. Mean engineering design process (EDP) task-specific self-concept scores for freshmen, sophomores, and seniors. Error bars show ±1 standard error.

The three classes rated themselves highly for most of the EDP task-specific self-concepts with an overall mean self-efficacy score of 76.1, mean level of motivation of 78.5, and mean level of expectation of success of 74.5. The students had a medium level of anxiety with a mean statistic score of 43.3. To determine if there was a difference for the four task-specific self-concepts by class, one-way ANOVAs were run using SPSS for each of the self-concepts with the subjects' class as the independent variable and the self-concept scores as the dependent variable. The difference in level of confidence between classes was not significant ($F_{self\text{-}efficacy}(2,59) = 0.228$, $p = 0.797$) and neither was the difference in the level of motivation ($F_{motivation}(2,59) = 0.735$, $p =$

0.484) or the expectation of success ($F_{expectation}(2,59) = 0.082$, $p = 0.922$). This signified that freshmen, sophomores, and seniors experience similar levels of confidence in performing engineering design tasks, motivation to complete the tasks, and expectation of success for the design tasks. If prior research on high self-efficacy holds true, all three classes of students should have persistence and perseverance when faced with engineering design tasks, which help to increase the surety of success in accomplishing the tasks. However, it is surprising that freshmen students have relatively high self-concept scores before taking a design course. It is also interesting to note that learning more engineering and becoming better prepared for design does not increase the students' self-efficacy or strengthen their expectation of success about the design process.

The only self-concept that was statistically significant was anxiety with $F_{anxiety}(2,59) = 3.688$, $p = 0.031$. Because there was a significance for anxiety, further tests were run to determine which classes had significant anxiety differences. Three a priori contrasts were completed to study the anxiety comparisons of freshmen and sophomores, freshmen and seniors, and sophomore and seniors. The tests showed that the seniors have significantly lower levels of anxiety compared to the sophomores ($p = 0.011$). However, there is not a statistically significant difference in anxiety level between freshmen and sophomores ($p = 0.443$) and freshmen and seniors ($p = 0.070$).

The only task-specific self-concept from the engineering design self-efficacy survey that is significant was the degree of anxiety in performing the tasks. On average, the seniors were significantly less anxious about design than the sophomores. Mechanical engineering students take their first design course in their senior year so it is possible that the students realized that design is easier than initially expected, thus lowering anxiety. If this was the case, it would be expected that students would have an increase in self-efficacy and a greater expectation of success. However, there is no change in the subjects' confidence and expectation, which suggests that there is likely another reason for the decrease in anxiety. A likely possibility is that the seniors have a more relaxed attitude towards school, engineering, and design since they are almost finished with their undergraduate education.

2. Task-Specific Self-Concept Scores and Ideation Effectiveness

Since there are four task-specific self-concept scores and four metrics to measure ideation effectiveness, there are sixteen possible relationships for each class. To begin the analysis to compare the task-specific self-concepts and the ideation metrics, scatter plots were created to examine the relationship. The plot of quantity compared to the self-concept scores for freshmen can be found in Figure 4. As can be seen, there does not appear to be an association between quantity and confidence, motivation, expectation of success, or anxiety. The other plots for the metrics and classes followed the same trend.

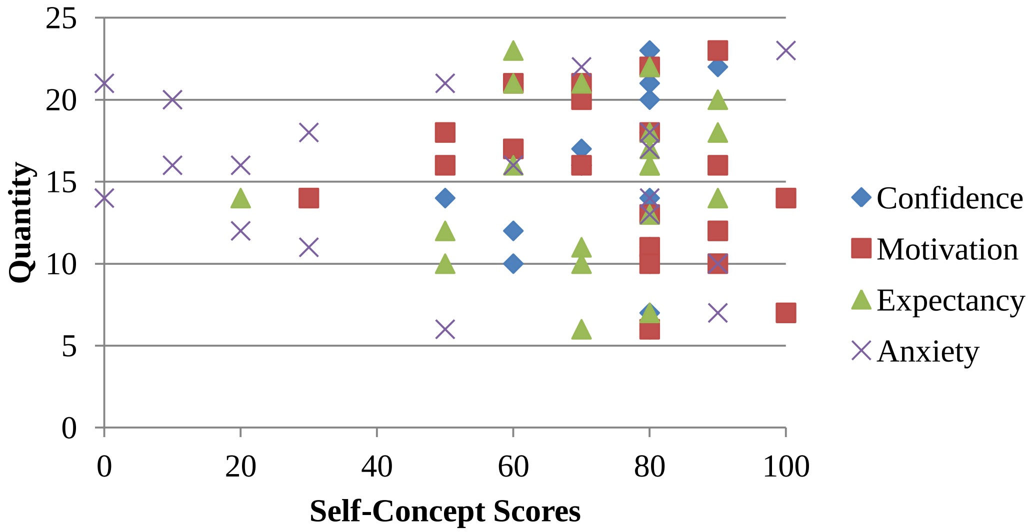

Figure 4. Scatter plot of the task-specific self-concept scores compared to quantity of non-redundant ideas for freshmen.

To determine if there was an underlying linear relationship, a regression analysis was completed. Comparing freshmen self-efficacy to the four ideation metrics yielded the output seen in Table 1. The table shows that none of the four ideation metrics were significantly linearly related to the self-efficacy of the freshmen since there is a minimum p-value of 0.131. The p-values for all of the regression analyses examining the four self-concepts and four ideation metrics for the three classes are summarized in Table 2. The p-values for quantity, quality, novelty, and variety from Table 1 were inputted in the self-efficacy row of the freshman table in Table 2 and eleven other regression analyses were run to complete the tables. For significance at the $p < 0.05$ level, it was found that there is no statistical significance for any of the relationships.

Table 1. Freshmen self-efficacy and ideation metric analysis output.

	B	SE B	β	F-value	p-value
(Constant)	141.947	69.509		4.170	0.059
Quantity	-0.246	0.535	-0.113	0.212	0.652
Quality	2.587	9.967	0.067	0.068	0.799
Novelty	-85.471	78.277	-0.281	1.192	0.292
Variety	93.310	58.375	0.431	2.554	0.131

Note: Significant at $p < 0.05$ level

Table 2. Summary of regression analysis showing p-values.

Freshmen	Quantity	Quality	Novelty	Variety
Self-Efficacy	0.652	0.799	0.292	0.131
Motivation	0.279	0.085	0.400	0.904
Expectation	0.887	0.513	0.786	0.082
Anxiety	0.513	0.607	0.697	0.906

Sophomores	Quantity	Quality	Novelty	Variety
Self-Efficacy	0.358	0.332	0.757	0.633
Motivation	0.952	0.850	0.565	0.675
Expectation	0.492	0.097	0.288	0.403
Anxiety	0.777	0.229	0.652	0.736

Seniors	Quantity	Quality	Novelty	Variety
Self-Efficacy	0.058	0.699	0.179	0.147
Motivation	0.059	0.795	0.196	0.178
Expectation	0.098	0.880	0.101	0.102
Anxiety	0.429	0.122	0.626	0.895

The fact that there is not an association between the task-specific self-concepts and the ideation metrics is surprising. It was expected that the students with high engineering design self-efficacy would be more successful in producing design solutions because they would put in additional effort. The students were told to generate solutions for the full time given so there should not be a difference in persistence. However, upon encountering an obstacle such as running out of ideas, it was expected that the high self-efficacy students would work harder to overcome the block. The design activity was anticipated to be a good measure of the students' design ability and those with high self-efficacy were hypothesized to generate a greater quantity of ideas with a large variety of high quality and novel solutions.

Perhaps the self-efficacy survey does not work well as a factor for design idea generation. The concept generation phase is one of the early stages of product design and requires creative thinking. Other self-efficacy surveys that showed a relationship to academic performance dealt with more concrete subjects and asked for outcomes with one "correct" answer such as solving division problems correctly[26], correctly answering mathematics problems[7], finishing homework assignments by deadlines[27], or correctly spelling all the words in a passage[28]. However, idea generation is more open-ended and does not have a method for individuals to assess their work or determine if their final solutions are "right" or "wrong". Higher self-efficacy may mean that more effort is applied once hitting a stumbling block; however, highly novel or high quality solutions take more than effort. Perhaps only more creative people can produce novel solutions and the self-efficacy survey cannot relate to this stage of design.

The engineering design self-efficacy survey may work better for the other stages of design since there are more concrete steps, including items such as identifying the customer need, prototyping and testing, and redesigning the product. Or perhaps the engineering design self-efficacy survey can only predict performance for the entire engineering design process as a whole. According to Pajares, the capabilities assessed and tested need to be similar in order to maximize the predictive power of self-efficacy beliefs[1]. Examining only the task of "develop design solutions" might be minimizing the influence of engineering design self-efficacy.

There are three other possible reasons for the discrepancy. First, the sample size of only 20 or 22 students per class might be too small to detect significance. Second, there may not actually be a relationship between design self-efficacy and design performance. The other possibility is that students may not be good judges of their design ability. Prior research has shown that there is a difference in idea generation performance and creativity between freshmen and seniors[29], but the freshmen and seniors have no significant differences in their self-concept scores. While the students' design skills change throughout their undergraduate education, they may not cognizant of the transformations.

Conclusion

This paper investigated engineering design self-efficacy, motivation, expectation of success, and level of anxiety of freshmen, sophomores, and seniors, and also examined how these task-specific self-concepts relate to ideation metric scores for a design activity. The between-subject controlled experiment found that there was not a significant difference in self-efficacy, motivation, and expectation of success. All classes scored these self-concepts highly. It appears that learning additional course material and becoming better prepared for design did not help to increase the task-specific self-concept scores as hypothesized, even though it was previously found that individuals' self-efficacy was built through engineering experience[2]. The level of anxiety for seniors was significantly lower compared to the sophomore anxiety level, although there was not a significant difference in the level of anxiety between freshmen and sophomores. There also was not a correlation between the task-specific self-concepts and the design ideation metrics. One possible reason for the lack of relationship is the small sample sizes, but it is also possible that self-efficacy may not be effective as a gauge for mechanical engineering concept generation design. Other possible explanations for the lack of predictability are that additional effort put forth by high self-efficacy students may not aid in creative pursuits, the self-efficacy instrument may only be an accurate predictor for engineering design as a whole, or the students may not be able to accurately gauge their ability.

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Appendix A

Design Problem - Device to Shell Peanuts

Problem Description:
In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:
- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Appendix B

Design Problem - Device to Aid in Shucking Corn

Problem Description:
Corn is currently the most widely grown crop in the Americas with the United States producing 40% of the world's harvest. However, only the loose corn kernels are used when bought canned or frozen in grocery stores. An ear of corn has a protective outer covering of leaves, known as the husk, and strands of corn silk threads run between the husk and the kernels. The removal of husk and silk to clean the corn is known as shucking corn. Design a device that quickly and cheaply shucks corn for mass production. Your goal is to create as many solutions to the problem as possible.

http://www.art-photograph-gallery.com/pictures-of-corn.html

Customer Needs:
- Must remove husk and silk from corn cob with minimal damage to kernels.
- A large quantity of corn must be shucked quickly.
- Low cost.