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Changing Creativity through Engineering Education and Bio-Inspired Design

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Abstract

With today's increasing competition and desire for innovation in our society, engineering schools must also improve students' creativity. However, according to a prior study (Genco, Holtta-Otto, Seepersad, 2012), the creativity of mechanical engineering students decreases over the course of an engineering program as measured through the originality of ideas for a design problem outside the mechanical engineering domain. In this paper we seek to answer two questions. First, how does the creativity of mechanical engineers change over time, as measured against four standard metrics of creativity – quantity, quality, variety, and novelty? Second, how do different bio-inspired design methods enhance student performance? This paper provides a high level summary of the project.

To answer the first question, we provide evidence from two data sets: a within-subjects and between-subjects longitudinal study that analyzes and compares students who have generated solutions for the same design problem during their freshman and senior years. For both the within-subject and between-subject data, there is an increase in the variety of solution and the number of high quality solutions. In contrast to the prior study, using a slightly different quality metric, we observe a decrease in average quality likely due to the participants searching a larger portion of the solution space. Also in contrast to the prior study, we observe no change in average novelty and an increase in the number of highly novelty solution found by seniors. The design problem within this study is clearly within the domain of mechanical engineering so it may be that students learn to be more creative as they progress through the engineering curriculum within their domain, but decrease in creativity for design problems outside their domain.

To answer the second question, we provide evidence from a biologically-inspired design course. This study, conducted over two semesters, evaluates the effects of a senior level Bio-Inspired Design course and various methods of performing bio-inspired design. Students learn 5 methods: Directed Method, Case Study, AskNature.org, BioTriz, and Functional Basis Keyword. Each method is compared through the quantity of ideas, quality, and number of solutions generated. The results show various strengths and weaknesses associated with each tool. The students were also given Carberry et al's Engineering Design Self-Efficacy survey before and after the course to assess the effects of the course. The results show increases in confidence, a high level of motivation, and decreases in anxiety in conducting engineering design.

Introduction

One of the main goals of engineering schools is to produce reputable engineers who have strong design skills and are good innovators. Students need to be creative and have high design self-efficacy. Self-efficacy is the extent of one's belief in one's own ability to complete tasks. With high self-efficacy, students will be more likely to select challenging tasks due to their self-confidence. An individual with higher self-efficacy is often willing to put in additional effort and is more persistent in solving the problem. Creative engineers generate new and valuable solutions to design problems. However, prior studies suggest that the creativity of mechanical engineering students decreases over the course of an engineering program. This paper investigates the latter claim, and searches for ways to increase creativity of engineering students.

Firstly, a four-year longitudinal study investigates the changes in design self-efficacy and design creativity of students in an engineering program[1]. Over the course of an engineering curriculum, the design self-efficacy and creativity of the students should increase. This longitudinal study tracked one cohort of students for four years, which resulted in two sets of data: within-subjects and between-groups data. Design self-efficacy, motivation, expectations of success, and the anxiety level of students were measured by Carberry et al.'s Design Self-Efficacy Instrument. Changes in design creativity study were measured using four standard metrics of design creativity: quantity of ideas, quality, novelty, and variety of solutions generated by students. The results from this study have shown that the engineering program measured, increases self-efficacy, expectations of success, and design creativity of students, while decreasing anxiety. However, the motivation of students did not change.

Secondly, a two semester study of a senior elective bio-inspired design course explored the effects of teaching engineering students various bio-inspired design methods [2,3]. Nature is a valid source to inspire creativity and innovation in design. Based on the claim that students' creativity decreases over the course of their engineering curriculum, this study seeks to counteract the claim by exploring ways to improve creativity in both the classroom and in real world applications through bio-inspired design. The course teaches 5 methods of bio-inspired design: Directed, Case Study, AskNature.org, BioTRIZ and Functional Modeling. These five methods are also compared to each other to highlight differences and advantages of using each one. For both semesters, Carberry et al.'s instrument is also used to determine the overall effectiveness of the course for impacting the student's design self-efficacy.

The results show that the engineering program measured and the elective course, both increase self-efficacy and expectations of success, while decreasing anxiety. However, the student's motivations did not change. The longitudinal study shows an increase in design creativity of students, while the elective course study displays effectiveness of using the five bio-inspired design methods to produce creative and high quality solutions.

Background

Teaching students to be innovative

While a number of design methods have been developed and are believed to support innovation, the empirical data is limited. It *is* known that teaching engineers a systematic method for design improves their design skills [4,5]. Though methods for teaching innovation have been explored, learning mechanisms for innovation remain poorly understood [6]. Using nature to inspire design is often cited as a method for innovation (e.g., Dryden, 2004). Recently, several groups of researchers have begun efforts to formalize bio-inspired design methods so that they can be broadly integrated in engineering education and practice [7-11]. Analogy, or taking ideas from existing designs, is used prolifically by practicing design engineers, especially when drawn from nature, as recommended by many design textbooks [12-16]. Research data strongly supports its impact on innovation [17-20].

Design Methods

The five methods used during the second study are the Directed Method, Case Study, AskNature.org, BioTRIZ and Function Modeling [2,3]. The Directed method is the most common and most researched [21-24]; it simply directs designers to draw inspiration from nature, based on the extent of their biological knowledge. The Case Study method directs designers to search biology databases and libraries for natural phenomena and through this exposure, draw analogies and transfer them to their design solutions. AskNature is an online database that documents biological phenomena and some applications to real engineering solutions [25]. The database base currently stores 1,800 natural phenomena, and accessibility is free to any user. BioTRIZ, derived from the “Theory of Inventive Problem Solving” (TIPS), categorizes various principles found in nature that solve common conflicts during engineering designs [26,27]. Functional Modeling directs designers to break down a design problem into its basic functions, which will allow for an easier analogy search in biokeywords-based biological databases such as DANE and IdeaInspire [28-30].

Design Problems

Design problems are used to effectively measure a designer’s ability to generate solutions and to effectively measure their creativity. The design problems utilized in the studies are referred to as Peanut, Alarm, Corn, Coconut, Blind Cup, Peach, and Iron Towel [2,3]. For Peanut, the designer has to generate ideas that shells peanuts with low cost, in high quantities. For Alarm, the problem asks to design an alarm clock that only wakes the user without disturbing anyone in the surroundings. Corn asks the designer to generate solutions to quickly remove the husk off a full ear of corn in an efficient way. Coconut asks to design a device to collect coconuts from trees in high quantity and efficiency. Blind Cup asks to design a measuring cup that can be utilized by a blind person and prevent unnecessary spills. Peach asks to design a device that removes the peach pit from peaches in large quantities and efficiently, without causing damage to the peaches. Lastly, Iron Towel asks to devise a solution to fold towels quickly and efficiently, mainly for hotel services.

Evaluation Metrics

To measure the effectiveness of the experimental conditions, four ideation metrics were used: quantity of ideas, quality of solutions, novelty of solutions, and variety of solutions. These metrics were introduced by Shah et al. [31] and further developed by Linsey et al. [32,33]. These metrics are used to quantitatively compare the experimental conditions based on the solutions generated by the participants. Quantity measures the number of non-redundant ideas generated by each participant. Quality measures the feasibility of a solution and how well it meets the criteria and customer needs provided for a specific problem. Novelty measures how unusual and unexpected a solution is when compared to the entire pool of solutions generated by the participants. Variety measures the size of the solution space spanned during the concept generation process.

Because problems can vary from one to another, the metrics were equated using the Linear Equating equation from ETS [34]. By making the problems equivalent, the results from different problems become comparable.

Experimental Methods

Longitudinal Study

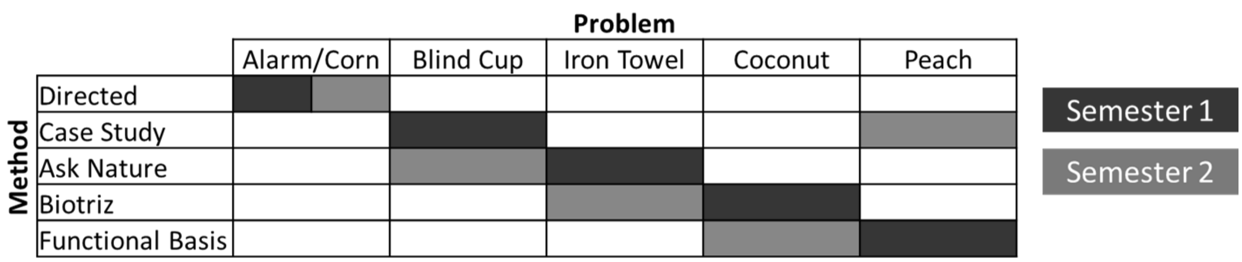
The four-year longitudinal experiment examines how the design self-efficacy and creativity of mechanical engineering students changes over time [1]. The experiment lasted from Spring 2011 to Spring 2014. Both the design self-efficacy and creativity studies have two separate pieces: within-subjects and between-groups data. The within-subjects study compares the results of students who generated solutions for the same design problem during their freshman and senior years. There were fourteen students for the within-subject data. The between-groups study compares the average results of students in different years of study (freshmen, sophomores, juniors, and seniors). For the design creativity study, the sophomores and juniors received different design problems than the freshmen and seniors. The Peanut problem was given to the freshmen and seniors for the within-subjects and between-groups studies. The Corn problem was given to sophomores for the between-groups study. The Coconut problem was given to the juniors for the between-groups study. These design problems were not equivalent; thus, they had to be scaled for accurate comparison.

The participants were undergraduate mechanical engineering students from Texas A&M University. In the within-subjects study, fourteen students participated in their freshmen and senior years. In the between-groups study, 158 freshmen, 46 sophomores, 46 juniors, and 74 seniors participated. While all junior and senior data collected were analyzed, only 44 random freshmen, 20 random sophomores were analyzed. Not all the collected data were analyzed due to time constraints. However, a minimum of 20 samples were used to make sure that the one-way analysis of variance would be robust to any of its assumptions and additional data would be analyzed if needed.

Bio-inspired Methods Study Procedure

The Bio-inspired Design Methods study collected data from the same elective course at Texas A&M, but during two different semesters, one year apart [2,3]. The five methods for bio-inspired design were taught throughout each semester as individual modules in the following order: Directed Method, Case Study, Asknature.org, BioTRIZ, and Functional Modeling. At the end of each module, the students were given an assignment containing a design problem, for which they were to generate solutions using the method of that module. In the first semester, there were 32 students, and 41 in the second. The methods and design problem were rotated from one semester to the other. Each method and their assigned problem by semester are summarized in Table 1.

Table 1: Graphical Representation of Experimental Setup of Methods and Problems



The participants were given a packet containing a design problem and customer needs. They were also surveyed to determine if they had seen or heard about the design problem prior to the experiment. They were asked to generate as many solutions as possible to the design problems for 50 minutes, while maximizing quality, novelty and variety. The participants were asked to sketch one design solution per page. In addition, the participants were instructed to create as many solutions as possible, while maximizing quality, novelty, and variety. For the longitudinal study, this experiment was conducted in class, while for the bio-inspired design methods study, the students were given a take home assignment. The solutions were then collected and analyzed by graduate students using the quantity, quality, novelty, and variety metrics.

Self-Efficacy Instrument

Each participant received the design self-efficacy survey by Carberry [35]. This survey serves to measure one's belief in their own capabilities to perform activities in order to successfully achieve a specific outcome.

Results and Discussion

Longitudinal Study

The evaluated metrics were analyzed for the between group studies each year and are graphically represented in Figure 1.

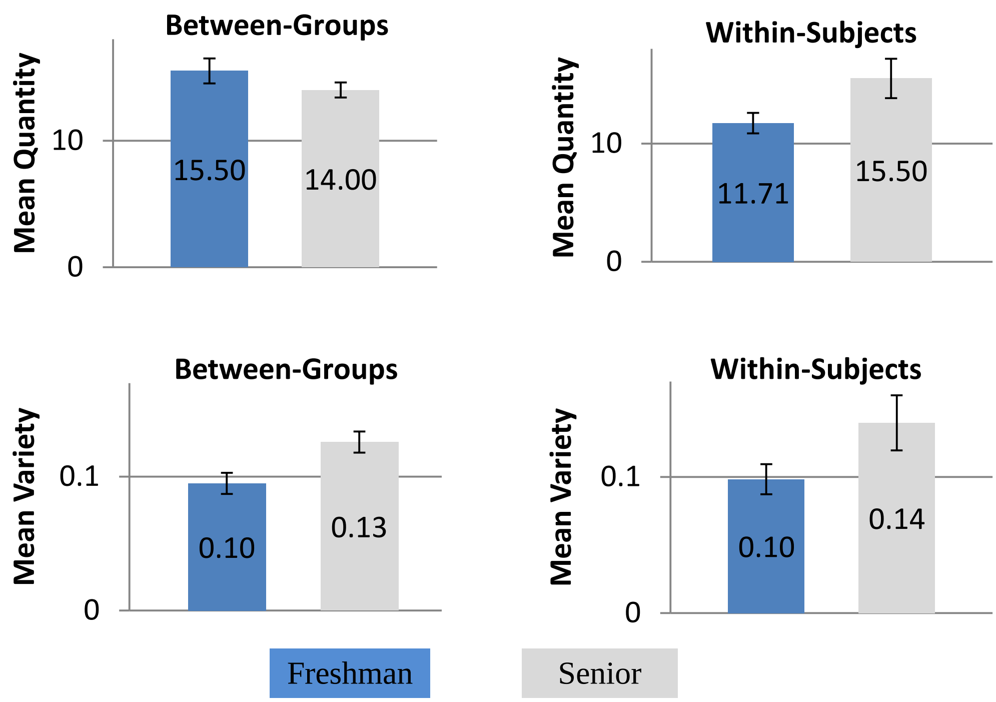


Figure 1: Between Group and Within Subject Mean Quantity and Variety Metric for Freshman and Senior Year (Error Bars: +/-1 SE)

The results from this longitudinal 4-year concept generation study indicate that creativity of engineering students increases during a mechanical engineering program. This is opposite of what was concluded from a prior study [36]. From the between group results, there is no significant difference between freshman and senior in the mean quantity of ideas (Mann-Whitney test, U = 1480, $p = 0.40$). However, the resulting pairwise comparison for the quantity metric show an increase in quantity of ideas from freshman to senior year (Wilcoxon signed-rank test, Z(13) = -2.77, $p = 0.01$). For both the within subject and between group results, the mean variety of solutions significantly increased from freshmen to seniors(Wilcoxon signed-rank test, Z(13) = -1.93, $p = 0.05$) and (Mann-Whitney test , U = 998, $p < 0.01$). This was expected because the seniors know more idea generation methods, such as methods of bio-inspired design.

The resulting mean scores from the self-efficacy surveys are summarized and displayed in Figure 2.

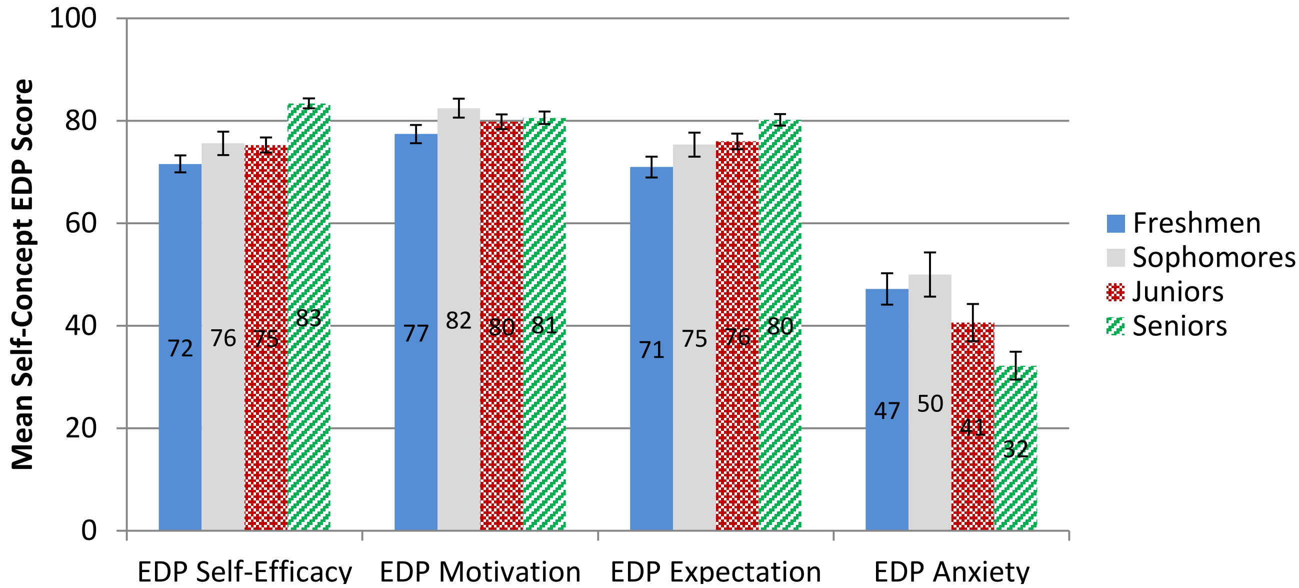


Figure 2: Between Group Mean EDP Self-Concept Scores for Freshman, Sophomore, Junior and Senior Year (Error Bars: +/-1 SE)

Three of the task-specific self-concepts, self-efficacy ($\chi^2_{\text{self-efficacy}}(3) = 37.40$, $p < 0.01$), expectation of success ($\chi^2_{\text{expectation}}(3) = 15.58$, $p < 0.01$) and anxiety ($F_{\text{anxiety}}(3,219) = 6.2$, $p < 0.01$), were found to be statistically significant in the between-groups analysis. The only task-specific self-concept that did not have a significant difference in either the within-subjects and between-groups comparisons was motivation; this was seen in both the overall data ($F_{\text{motivation}}(3,219) = 1.7$, $p = 0.2$) and the within-subjects data ($t(11) = 0.6$, $p = 0.5$). This demonstrates that freshmen, sophomore, juniors, and seniors experience similar motivation levels when it comes to engineering design. This may be due to the fact that engineers begin their undergraduate career with a high level of motivation, and there is not much room for improvement in that area. The within subject pairwise results also showed the same trends from freshman to senior with high statistical significance for self-efficacy, expectancy, and anxiety. Furthermore, there is still no difference between freshman and senior year for motivation, despite the pairwise comparison.

Bio-inspired Design Methods Study

Students were able to use all of the methods to create solutions. For this study, only the quantity and quality metrics were evaluated with the addition of number of solutions. The latter determines the average number of solutions, as a whole, that each participant generated. In general, the all the metrics show Functional Modeling to be the lowest when compared to the other methods. This may have been due to the fact that the method was more challenging to use as it was time consuming and the bio-keyword data base did not function properly. However, the other four vary slightly. For the mean quality, there is no significance between Directed, Case Study, AskNature and BioTRIZ.

Figure **3** shows the comparison of methods based on the mean quantity of ideas provided and number of solutions generated. Based on these results of the Kruskal-Wallis test, χ^2 = 86.6 df = 4, $p < 0.001$ and χ^2 =51.96, df = 4, $p < 0.001$, respectively, there is a significant difference across the different methods.

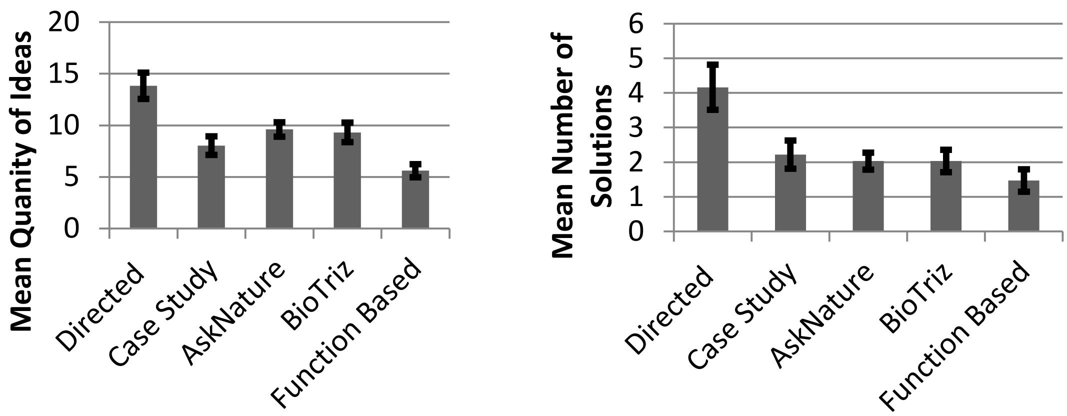


Figure 3: Mean quantity of ideas and number of solutions comparison across methods Error Bars: +/-2 SE

Of the five methods, the Function Based method provides a statistically significant lower mean quantity of ideas than the other four (Mann-Whitney U test, p < 0.001*)*, and the Directed method provides a statistically significant higher mean than the other four (Mann-Whitney U test, p < 0.001*)*. There is no statistically significant difference between Case Study, AskNature and BioTRIZ. For mean number of solutions, the Directed method provides a statistically significant higher mean than the other four (Mann-Whitney test, p = 0.012*)*. However, there is no statistically significant difference between Case Study, AskNature and BioTRIZ, so there is no conclusive different among those three methods in terms of the number of solutions (Mann-Whitney test, p > 0.95).

When comparing the Pre-Course and Post-Course self-concept scores in Figure 4, the students show a clear increase in their self-efficacy, expectancy, a slight decrease in anxiety, and no difference in high motivation. For both self-efficacy and expectancy, there is a statistically significant difference (p < 0.001). Though for anxiety, it is nearly significant (p = 0.098). Overall, the course shows to have a positive effect on the student's self-efficacy.

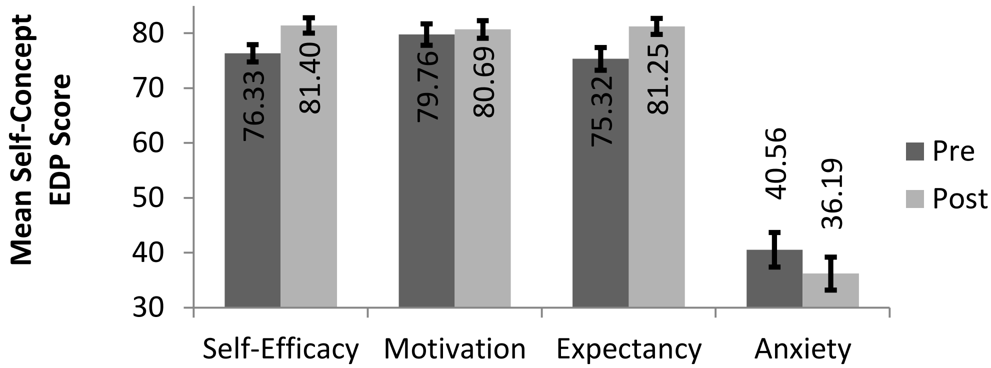


Figure 4: Pre And Post EDP Self-Concept Scores For Combined Semester 1 And 2 Data Sets

Conclusions

The four-year longitudinal study examined the changes in design self-efficacy, motivation, expectations of success, level of anxiety, and design creativity of students. The quantity of ideas, variety of solutions, number of high novelty, and sum of quality of solutions generated by students increased significantly. On the contrary, the average quality and number of high quality solutions decreased over time. This is because seniors produced more novel solutions and explored a larger variety of solutions, which were not necessarily high quality. There were solutions that were very creative but did not receive high quality scores because they were not technically plausible. The self-efficacy and expectation of success of students significantly increased during the study. This shows that the students gain more confidence as they advance in the curriculum. On the other hand, the anxiety of students decreased. Lower anxiety may be due to an increase in confidence, experience from completed coursework, and internship or full-time job offers. However, the motivation of students remained constant, which means that they experience similar motivation levels when performing projects. This may be due to the fact that freshmen start school with a high level of motivation, which remains high throughout their education. This study has discovered that an engineering program is able to produce valuable engineers by increasing their self-efficacy and creativity.

The bio-inspired design methods study examined the effectiveness of the five different methods. While there are slight differences between the methods, each one helped students find high quality and creative solutions to problems. Further investigation needs to take place to further understand the impact of each method. Moreover, the linear conversion factor may not be a particularly effective way to equate the scores because there are other more complex dimensions that need to be taken into account, such as the domain of the problem and complexity of the problem [37,38]. The designer may have a higher level of familiarity with a specific problem and facilitates the generation of effective ideas.

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