AC 2010-1221: AN EXPERIMENTAL INVESTIGATION OF THE INNOVATION CAPABILITIES OF ENGINEERING STUDENTS

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An Experimental Investigation of the Innovation Capabilities of Engineering Students

Abstract

One of the greatest challenges facing engineering education is the need to educate engineers who can innovate successfully. With increasing calls for enhancing the level of innovation in the national economy, the role of innovation in engineering education is often underemphasized and poorly understood. In this experimental study, we compare the results of concept generation exercises completed by freshman- and senior-level mechanical engineering students. Students were asked to use a modified 6-3-5/C-sketch method to generate concepts for a next-generation alarm clock. Senior-level students were divided into control and subject groups who implemented the standard 6-3-5/C-sketch method and a version of the method enhanced for creativity, respectively. Resulting concepts were analyzed using metrics for novelty, fixation, and quality. The results indicated that the freshman students produced more novel concepts and were less fixated on the sample clocks shown in the experiment. Both freshman and senior groups produced concepts with similar (high) levels of quality and feasibility. The results support the troubling conclusion that freshman engineering students are more innovative than seniors. This conclusion highlights the need for increased emphasis on innovation and creativity in the engineering curriculum.

Introduction

One of the greatest challenges facing future engineers involves creating innovative products that are competitive in global markets.[4,10,12] Despite the accompanying calls for innovation and creativity in engineering education, creativity is still not considered a key part of engineering education.[3,20] However, there is evidence that although engineering and non-engineering freshman are equally creative,[7] graduating engineers may not be as creative as expected. In fact, freshmen seem to be more capable of solving ill-defined problems that require creative thinking than senior-level engineering students.[42] In this paper, the creative outputs of senior and freshman engineering students will be compared, based on the results of a series of controlled concept generation experiments.

Background

Attainment of engineering skill follows a pattern of skill acquisition that is relevant to many domains. The freshman and sophomore years typically represent the first stage, known as the cognitive stage, which involves encoding a skill or learning a set of facts relevant to the skill.[15] In engineering, this stage includes acquiring mathematical skills such as calculus, physics principles such as Newton's laws, and engineering fundamentals such as strength of materials and fluid mechanics. When first learning engineering skills relevant to design, students must repeat these principles as they perform design-related tasks. The next stage, the associative stage, involves a transformation from declarative (fact-based) knowledge to procedural knowledge.[2] Errors in developing engineering designs are significantly reduced during this stage as students gain practice in design. For example, students may become more familiar with appropriate design choices such as the use of supportive ribs to strengthen structures or particular material choices for a specific manufacturing process. The final stage, or autonomous stage, involves the transformation of procedures from controlled to automatic processes.[33] This stage relies on significant amounts of practice. Expert engineers[14] are generally performing at the autonomous level of skilled performance.

Although the acquisition of skill within the engineering domain helps students increase the quality of their designs, it can also decrease the creativity of their designs. As an early example, Guilford[16] found a curvilinear relationship between intelligence and creativity. People at lower levels of intelligence were unlikely to be creative because they did not possess enough knowledge. However, people at higher levels of intelligence were not always creative. Although they possessed high amounts of intelligence and skill, they showed a wide range of creative output, from lack of creativity to high amounts of creativity. Some authors have suggested that highly skilled individuals may have trouble adapting their thinking in order to produce creative works.[13,40] The evidence suggests an inverse relationship between skilled performance and creativity. Wiley[41] showed that high levels of knowledge hindered performance on remote associates problems, in the form of a classic creativity test regarding baseball problems.[21] Bilalić[6] found that experts became fixated on a familiar solution in a game of chess, thus showing inflexibility in thought. Ball[5] found that senior engineers tend to approach problems breadth-first, reviewing many design solutions before narrowing on one, whereas junior engineers tend to use a less creative depth-first strategy.

Because creativity is assumed to be a necessary precursor of innovation, it is taught primarily as a set of concept generation methods as part of a junior- or senior-level design class. There are numerous concept generation methods including 6-3-5[25], C-sketch[34], TRIZ[1], Design by Analogy[19], and six hats[11] to name a few. One aim of these creativity methods is to prevent *design fixation.* Design fixation can be defined as an unintentional adherence to a set of features or concepts limiting the output of conceptual design.[17] Design fixation is typically measured as similarity to the design brief to which the designers were exposed prior to concept generation. Designers often tend to remain fixated even when they are instructed not to copy the features in the design brief or when they are subjected to a time delay between the exposure and the design task.[8,17,23,30,38] It has also been shown that designers who are more familiar with the object of a design task are more prone to copy the features in a design brief[30] or set of existing designs.[27]

Many researchers have compared creativity methods to evaluate their effectiveness in an engineering design context. In multiple studies, Mullen et al.[22] found that the productivity of group brainstorming is lower than the combined productivity of individuals working alone, as measured by the quality and quantity of ideas generated. However, when the technique is switched from brainstorming to brainwriting,[26] a significantly higher quantity of unique ideas is found when designers exchange ideas rather than work alone. Shah and coauthors[34,35] compared three group concept generation techniques: C-Sketch, 6-3-5, and the Gallery method (in which designers work on ideas individually, post the written ideas for the group to view and discuss and then repeat the process). They found that C-Sketch outperformed the other two methods on several criteria, including the quality, novelty, and variety of ideas generated. C-Sketch relies on silent exchange of written sketches, rather than the text-based descriptions dictated by 6-3-5, and without any of the verbal discussion promoted by the Gallery method. Linsey[19] confirmed the conclusion of Shah et al. that rotational viewing produces more ideas than gallery viewing, in which everyone's designs are posted on a wall periodically for viewing and discussion. Weaver further showed that combining a modified 6-3-5 method with pre-concept generation defixation exercises can further improve the outcome.[39] In summary, past research seems to support the use of the modified 6-3-5 method suggested by Otto and Wood[24], in which 3 ideas, expressed by combinations of sketches and phrases, are generated silently by each of the 6 participants and rotationally exchanged 5 times with a group of collaborating designers.

Based on the results of past research, modified 6-3-5 was chosen as the concept generation technique for this study. This method requires each of six participants to independently create three concepts. Each concept may be described with a combination of sketches and text. After each participant creates three concepts, the concepts are rotated throughout the group. Each participant, in turn, has a chance to view and edit the concepts. The cycle ends when concepts return to their original authors.[24]

Research Method

Students were divided into two groups for a subject-control experiment. The students in both subject and control groups were told to assume that they were working for a design company and that their client has asked them to design a next-generation alarm clock. Both groups of students used the modified 6-3-5 method to generate concepts for the next-generation alarm clock, after interacting with two standard alarm clocks. The control groups simply interacted with the alarm clocks freely. The subject groups were introduced to a defixating technique called Extreme Experience Design (EED). The EED exposes the participants to an extreme experience with the product, by altering their senses through the use of disabling devices. In this experiment the disabling devices included blindfolds, ear plugs with ear muffs, and oven mitts. Subject group participants were instructed to interact with the product freely, as long as they tried each of the disabling tools for a brief period. The intent was to defixate them from the basic alarm clock in front of them and open their minds to more alternative ideas.

The students in both subject and control groups were given up to 20 minutes to interact with the alarm clocks before beginning the modified 6-3-5 method for concept generation. While interacting with the alarm clocks the students worked together and engaged in discussion. Once the interaction phase ended and the concept development phase began, students were forbidden from talking. Students spent 15 minutes developing their original three concepts and 10 minutes modifying other students' concepts according to the modified 6-3-5 method.

Measuring Creativity and Feasibility of the Concepts

In this study we chose to measure the creative outcome rather than the creative personality of an individual because the outcome is usually most important in engineering applications. There are several ways of measuring the creative outcome of a concept. Shah et al.'s novelty metric[36] is commonly used in engineering and was thus chosen for the innovative measurement criteria of this study. Before the metrics could be applied, each concept was analyzed holistically and decomposed into a set of features. Once a set of features was identified it was then divided into a subset of basic features and a subset of additional features. The set of basic features was based on the primary function of the alarm clock and included mode of alarm, display type, information shown, mode of input, energy source, and snooze. The set of additional features included music, shape/layout, and additional functions (e.g., making coffee). The set of features was created after the concept generation exercise to ensure that it was comprehensive enough to capture important aspects of the resulting concepts. Evaluating concepts at the feature level facilitates accounting for multiple innovative aspects of a design and helps promote consistency and repeatability between concepts and evaluators.

The level of creativity in each concept was measured with Shah et al.'s novelty metric,[36] which was applied at the overall concept level and at the feature level. We analyzed each concept and determined which features the concept possessed (e.g., beeping as a mode of alarm, a battery as an energy source, a coffeemaker or fish tank as an additional function, etc.). After the features were identified for each concept, the novelty metric was applied to each feature. The novelty metric is calculated according to Shah et al.[36] as follows:

$$S_j = \frac{T_j - C_j}{T_j} \times 10 \tag{1}$$

where T_j is the total number of concepts produced, C_j represents the number of times the current solution appears for that feature, and all of the features are weighted equally.[36] For example, if ten concepts were produced and four of them had vibrating alarms then the novelty score for the alarm feature for would be 6. The scores can range from 0-10, with10 being the most novel.

Using the same set of features, we were also able to measure feasibility using Shah et al.'s quality metric, as embodied in the flowchart in Figure 1.[36] For example, suppose an alarm clock was designed with a snooze button that shocks you. Is it technically feasible? Yes. Is it technically difficult for the context? No, resulting in a score of 10 for technical feasibility. The quality metric was performed for all features.

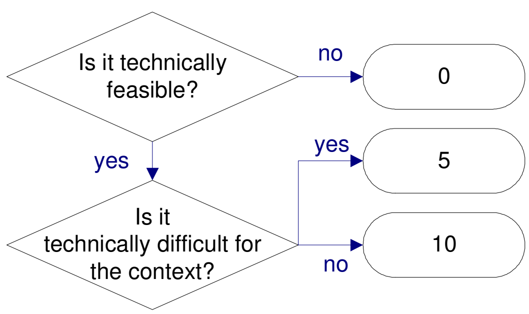

Figure 1: Flowchart for Analyzing Concept Quality

In addition to the above metrics, an additional metric was used to measure the conformity of generated concepts to features of the prototype to which the designer was exposed prior to the ideation task. The measure of design fixation is similar to design fixation metrics proposed in the literature.[38,40,41] Specifically, conformity is calculated as follows:

$$M_{conf} = \frac{N_{features\_same\_as\_in\_prototype}}{N_{total\_features\_in\_prototype}} \tag{2}$$

where M_{conf} measures the fraction of feature types (i.e., solution principles for specific features) in the concept that match feature types in the prototype. The students in this study were shown two different alarm clocks. The first alarm clock had a beeping alarm, a digital lit display, buttons for input, a back-up battery in addition to an electric plug, and a snooze button. The second alarm clock was a simple analog clock, with a beeping alarm, a wall plug, dials for input and no snooze feature. Neither clock had the capability of playing music or performing any other functions.

To illustrate the use of the metrics, the metrics are applied to the concepts illustrated in Figures 2-4. The first concept (Figure 2), was selected from the freshman group of concepts. This clock was designed to have a vibrating pad that the user can slip underneath a pillow to vibrate when the alarm goes off. Also, when the alarm is activated, the user's television is turned on as a second mode of alarm. The alarm clock has a large display and can be controlled remotely from a distance as well as through the use of standard buttons. The alarm clock was designed to have a radio as well as to allow music to be input by the user through the SD card slot.

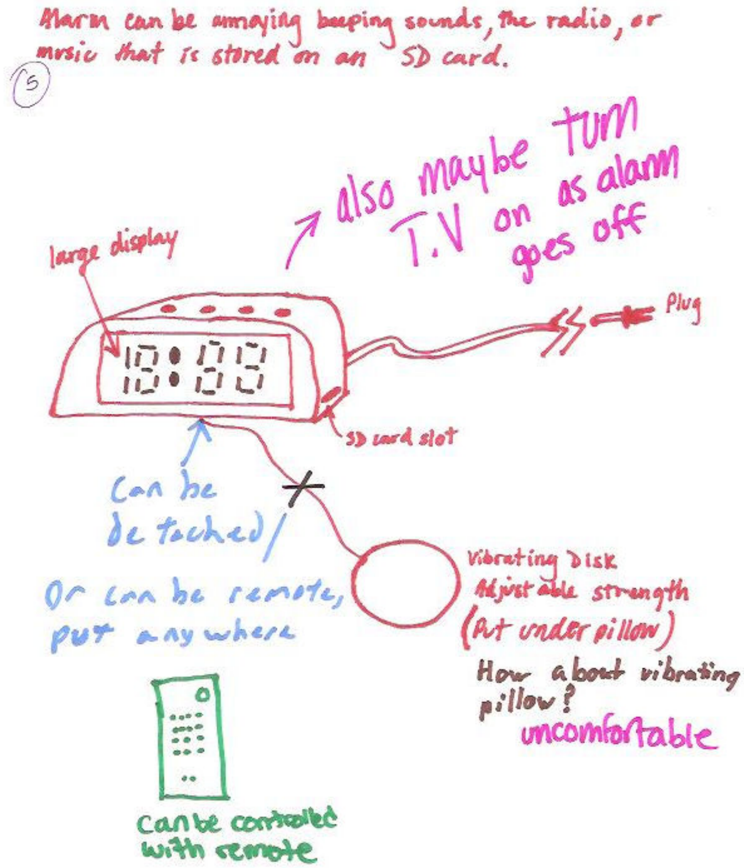

Figure 2: Sample Freshman Engineering Student Concept

The clock shown in Figure 3 was developed by a set of students in the senior-level control group. This clock does not specify how it wakes the user so it is considered to be a standard beep or radio alarm. It has a standard display time, along with a button that allows the user to access traffic information. It is a standard button-activated alarm clock with your average snooze button. The clock comes equipped with a radio as well as nature sounds to help comfort the user.

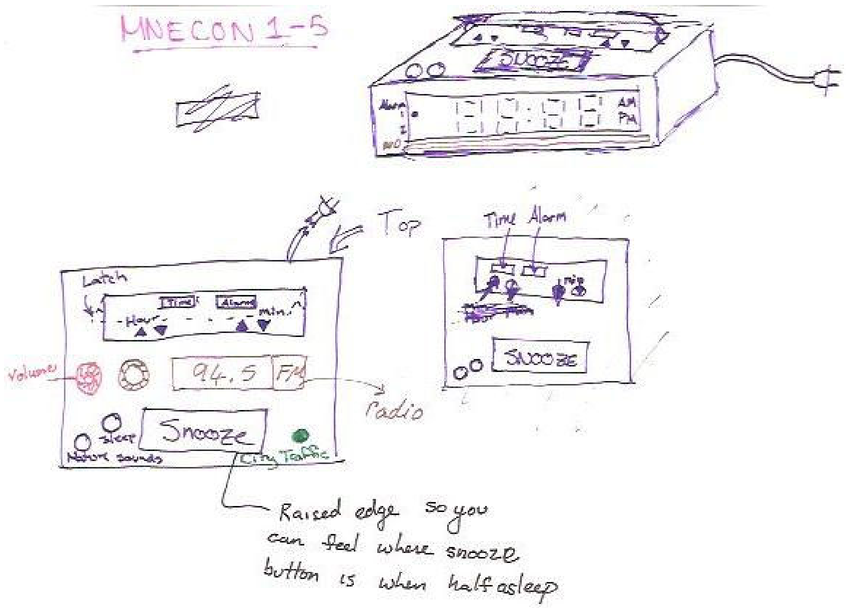

Figure 3: Sample Senior Control Group Concept

The last clock concept, shown in Figure 4, is a sample from the senior-level subject group. The concept in Figure 4 is a projector/alarm clock combination. It displays video on screen in the user's bedroom. It responds to inputs through a remote as well as a motion input. It hangs from the ceiling and is wired into the home electrical system to receive electricity.

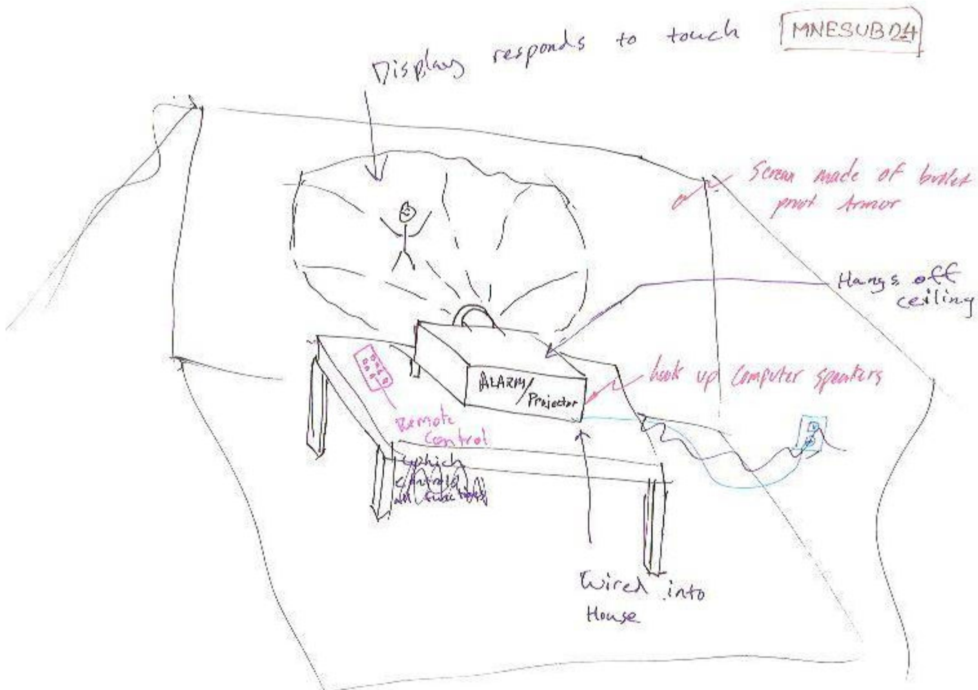

Figure 4: Sample Senior Subject Group Concept

To illustrate the application of the metrics to the sample concepts, we begin by identifying the features of the alarm clocks, as outlined in Table 1. In Table 1, a "standard" entry indicates that the implementation of the feature in the concept is very similar to that of one or both of the prototype clocks introduced to the participants at the beginning of the study or one that is commonly available in the market.

	Freshman Concept	**Senior Control Concept**	**Senior Subject Concept**
Basic Features:			
Mode of Alarm	vibrates and turns on the television	Standard	standard
Display Type	large	Standard	projection
Information Shown	standard	Traffic	standard
Mode of Input	remote	Standard	remote/motion
Energy Source	standard	Standard	standard
Snooze	none	Standard	none
Additional Features:			
Music	combo	Live	standard
Alternative Use	standard	nature sounds	projector
Shape/Layout	disk	Standard	ceiling

Table 1: Features of Sample Concepts

After features are analyzed, novelty scores are calculated for each group of participants. Table 2 displays the novelty scores for each feature, as well as the total novelty and basic novelty score for each concept. There were a total of 78 freshman concepts, 47 senior control concepts and 63 senior subject concepts. The novelty score for each concept is calculated based on a comparison with other concepts generated by the same group of participants. For example, 2 of the 78 concepts in the freshman group used either vibration or television as their mode of alarm. Therefore, the novelty score for the alarm mode for the freshman concept is calculated according to Equation (1) as follows:

$$9.7 = \frac{78-2}{78} \times 10 \tag{3}$$

Novelty scores are calculated similarly for the rest of the features of each concept. The basic novelty score for the overall concept is calculated by averaging the novelty scores for the basic features. The total novelty score for each concept is calculated by averaging the novelty scores for *all* of the features, including the three additional features.

	Freshman Concept	Senior Control Concept	Senior Subject Concept
Basic Features:			
Mode of Alarm	9.7	6.7	6.6
Display Type	8.6	1.3	8.3
Information Shown	1.9	9.7	1.7
Mode of Input	9.7	2.0	9.7
Energy Source	2.8	1.0	1.0
Snooze	7.2	5.3	6.2
Additional Features:			
Music	8.3	9.3	1.7
Alternative Use	3.6	9.7	9.7
Shape/Layout	9.7	6.0	9.7
Scores:			
Total Novelty	6.9	5.7	6.1
Basic Novelty	6.7	4.3	5.6

Table 2: Novelty Scores for Sample Concepts

	Freshman Concept	Senior Control Concept	Senior Subject Concept
Basic Features:			
Mode of Alarm	10	10	10
Display Type	10	10	10
Information Shown	10	5	10
Mode of Input	10	10	5
Energy Source	10	10	10
Snooze	10	10	10
Additional Features:			
Music	10	10	10
Alternative Use	10	10	10
Shape/Layout	10	10	10
Scores:			
Total Quality	10	9.4	9.4
Basic Quality	10	9.2	9.2

Table 3: Quality Scores for Sample Concepts

Table 3 tabulates the quality metric results for each of the concepts. Most of the features for all of the concepts received scores of 10, which indicates that these features are technically feasible and are not technically difficult for the context. One exception is the senior control group’s concept, which offers a feature to display traffic information on demand. This is technically feasible and can be accomplished through the use of a satellite radio, for example, but it may be technically difficult to obtain real-time traffic information for any random town across the country. The mode of input for the senior subject group’s concept also received a quality metric less than 10. Although motion sensors do exist, they are not used in many alarm clocks and are technically difficult for the context as compared to the standard use of buttons, resulting in a score of a 5 for the motion and remote controlled mode of input.

	Sample Alarm Clock	**Freshman Concept**	**Senior Control Concept**	**Senior Subject Concept**
Basic Features:				
Mode of Alarm	standard	vibrates and turns on the television	standard	standard
Display Type	standard	large	standard	projection
Information Shown	standard	standard	traffic	standard
Mode of Input	standard	remote	standard	remote/motion
Energy Source	standard	standard	standard	standard
Snooze	standard or none	none	standard	none
Additional Features:				
Music	none	combo	live	none
Alternative Use	none	none	nature sounds	projector
Shape/Layout	standard	disk	standard	ceiling

Table 4: Conformity Comparison for Sample Concepts

	Sample Alarm Clock	**Freshman Concept**	**Senior Control Concept**	**Senior Subject Concept**
Basic Features:				
Mode of Alarm	standard	0	1	1
Display Type	standard	0	1	0
Information Shown	standard	1	0	1
Mode of Input	standard	0	1	0
Energy Source	standard	1	1	1
Snooze	standard or none	1	1	1
Additional Features:				
Music	none	0	0	1
Alternative Use	none	1	0	0
Shape/Layout	standard	0	1	0
Scores:				
Conformity	-	4/9 = 4.4	6/9 = 6.7	5/9 = 5.6

Table 5: Conformity Scores for Sample Concepts

The conformity metric is based on a comparison of the concept clocks to the sample, prototype clocks used in the experiments, as documented in Table 4. Each feature is assigned a 1 if it matches the sample alarm clock and a 0 if the feature differs. The overall conformity score for a concept is obtained by averaging the conformity scores for each feature of the concept. Higher scores indicate greater similarity to the sample clock. Conformity results for each of the three concepts are provided in Table 5.

Results

All of the concepts generated by the freshman, senior control, and senior subject groups were analyzed by one of the researchers. The metrics were applied to all of the concepts by a single evaluator in order to maintain consistency amongst the scores.

One-way ANOVA was used to compare results between groups of participants. Figure 5 illustrates the total novelty scores for the senior control and senior subject groups. Total novelty scores are based on the entire features list, with higher scores indicating greater novelty.

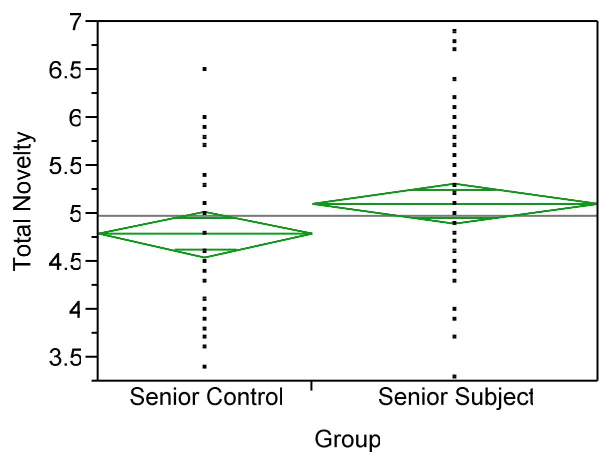

Figure 5: Total Novelty Score for Senior Control and Subject Groups

In Figure 5 the horizontal line represents the mean of the entire sample set. The line in the center of each diamond represents the mean for each group, and the difference between the top peak and the bottom peak of each diamond represents a 95% confidence interval. The small lines at the bottom and top of each diamond are called overlap marks. These overlap marks are used to help determine if the means of the two groups are statistically different at the 95% confidence interval. As shown in Figure 5, the difference in novelty scores between the senior control and senior subject groups is statistically significant (with a t-statistic of 1.933, assuming unequal variances, and a P-value of 0.0548). As shown in Figure 6, the novelty score was calculated for the basic features only. The difference in novelty scores is not statistically significant (with a t-statistic of 1.0238 and a corresponding P-value of 0.3073). Although the senior subject group has a higher average novelty score than the senior control group, there is no statistical difference for the basic features alone.

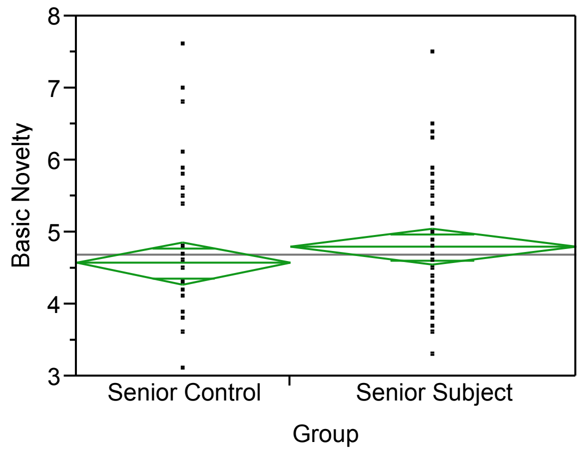

Figure 6: Novelty Score for Basic Features for Senior Control and Subject Groups

These results indicate that the subject group's innovative features were mostly found in the additional features of the clock (music, additional function, and shape and layout) rather than the basic functions. Defixating the students in the subject group helped them to be more creative and innovative by adding additional functions and changing the form of the clock, as observed in the wristband concept.

We then repeated the novelty analysis with the freshman engineering students. The comparative analysis of the freshman and senior control groups is illustrated in Figures 7 and 8. The results are identical to those of the senior control and subject group comparison. The freshman group earned a significantly higher total novelty score (t-statistic of 5.4414, P-value less than 0.0001), but there was no statistically significant difference in novelty scores for the basic features only (t-statistic of 0.1355, P-value of 0.8923).

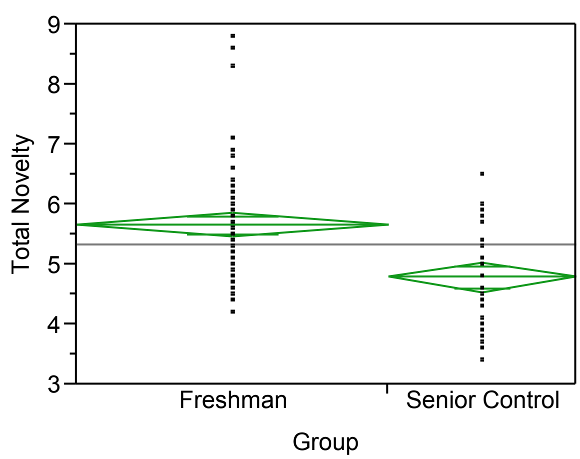

Figure 7: Total Novelty Score for Freshman and Senior Control Groups

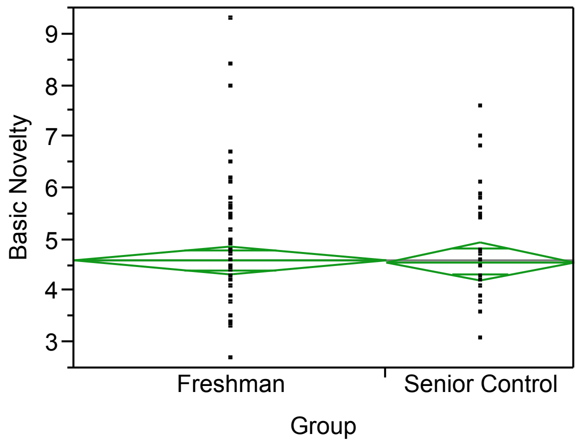

Figure 8: Novelty Score for Basic Features for Freshman and Senior Control Groups

We also analyzed the technical feasibility or quality[32] of the concepts. There was some suspicion that a higher novelty would inversely correlate with the quality of the concepts, but this hypothesis was not supported by the data. Quality scores were calculated for all features (total quality) and for basic features only (basic quality). These quality scores were calculated for the senior control, senior subject, and freshman groups, as illustrated in Figures 9 through 12. Analysis at the total quality level showed that there was no statistically significant difference between the senior subject group and the senior control group, as illustrated in Figure 9 (total quality t-statistic of 0.6899 and P-value of 0.4911), or between the senior control group and the freshman group, as illustrated in Figure 11 (total quality t-static of 1.63347 and P-value of 0.1041).

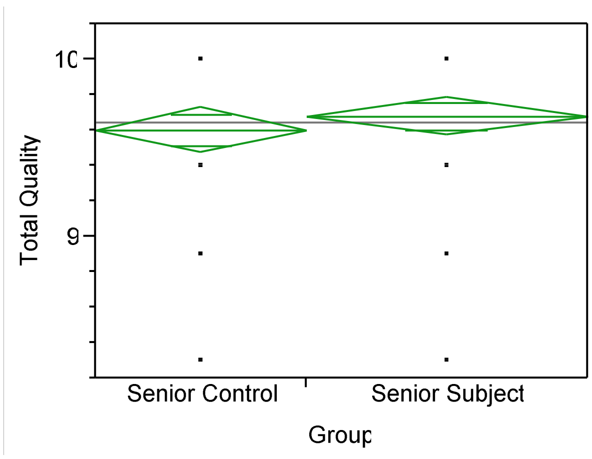

Figure 9: Total Quality for Senior Control and Subject Groups

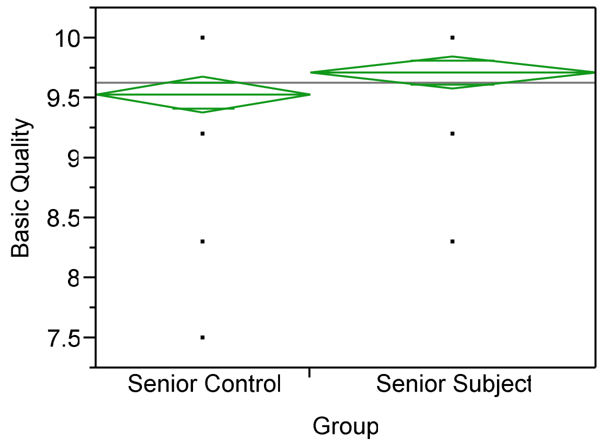

Figure 10: Basic Quality for Senior Control and Subject Groups

However, when the t-test was run for the basic features only, the results showed a statistically significant difference in the means of the freshmen group and the senior control group. The senior control group had a lower quality score (with a t-statistic of 2.4133 and a P-value of 0.0168). The freshman concepts averaged a score of 9.80 for basic quality and the senior control group a score of 9.53.

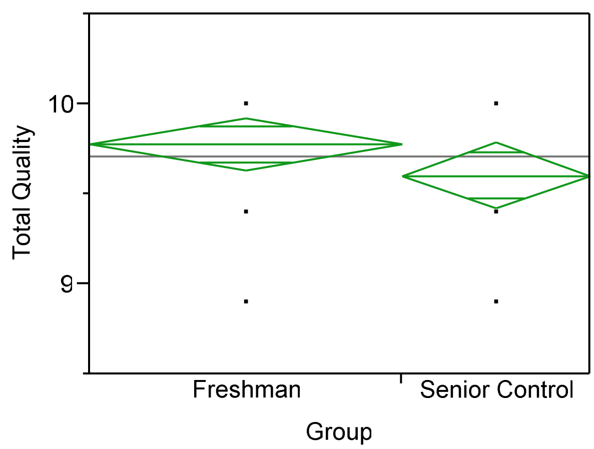

Figure 11: Total Quality for Freshman and Senior Control Groups

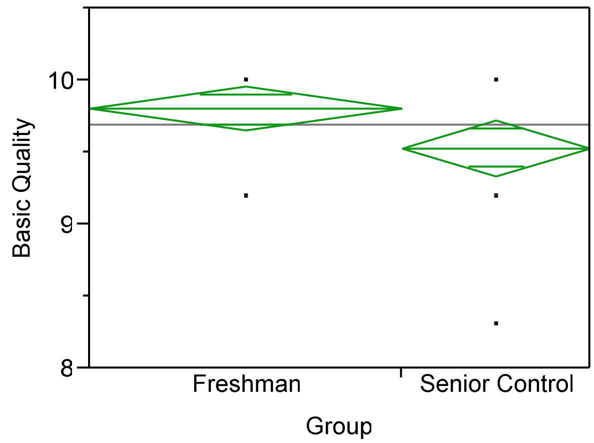

Figure 12: Basic Quality for Freshman and Senior Control Groups

We also completed a fixation or conformity analysis to investigate how similar the generated concepts were to the sample clocks used in the experiment. A higher score indicates a higher level of fixation on the sample alarm clocks. In Figure 13 below senior control and senior subject groups seem to score almost equivalently in the fixation metric. This supports the earlier finding of fixation remaining even after defixation techniques are used. [8,17,23,30,38]

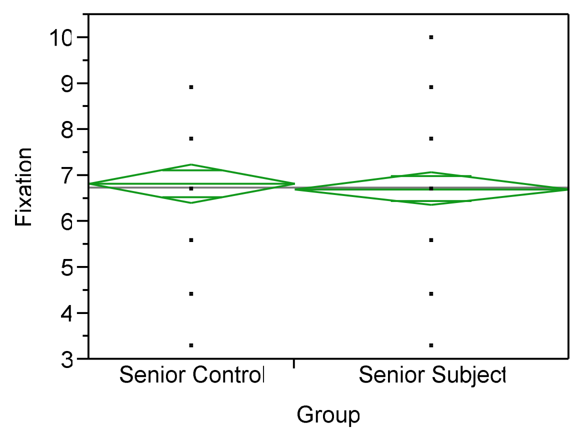

Figure 13: Fixation for Senior Groups

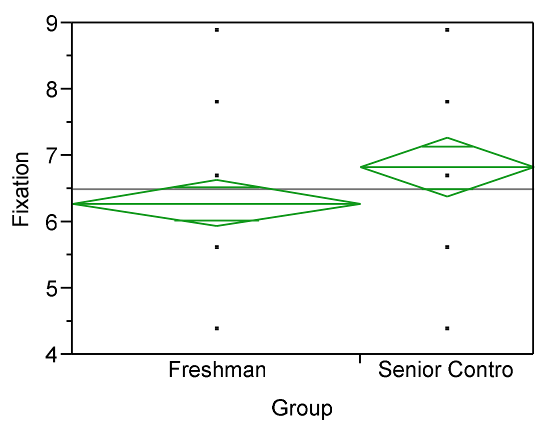

Figure 14: Fixation for Freshman Vs. Senior Groups

The senior control group has a fixation mean of 6.83 and the freshmen group has a fixation mean of 6.29, as shown in Figure 14. This difference is significant with a t-statistic of 1.9287 and a P-value of 0.0553. The result shows that the senior control group is more fixated than the freshman group and that the concepts they created conform more closely to the sample clocks used in the study.

Lastly, we can compare all three data sets at once. As shown in Figures 15, 16, and 17, the freshmen appear to be more creative than the defixated senior students. To investigate the findings more closely, we ran a student's t-test on the novelty scores for all three groups. The mean scores for the freshman group, senior control group, and senior subject group were 5.66, 4.79 and 5.11, respectively. At an alpha value of 0.1, the pair wise differences between all three groups were significant.

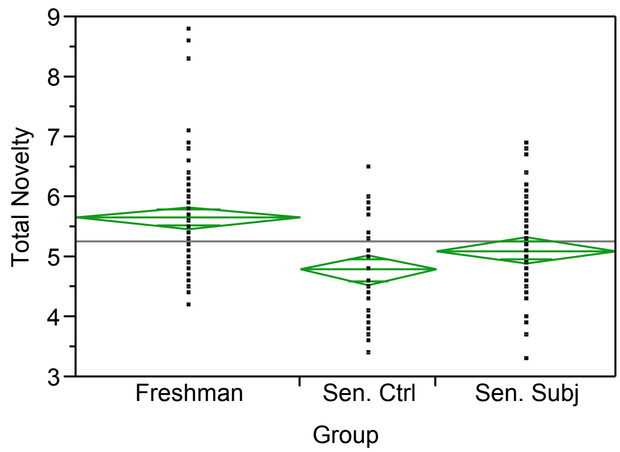

Figure 15: Total Novelty for All Groups

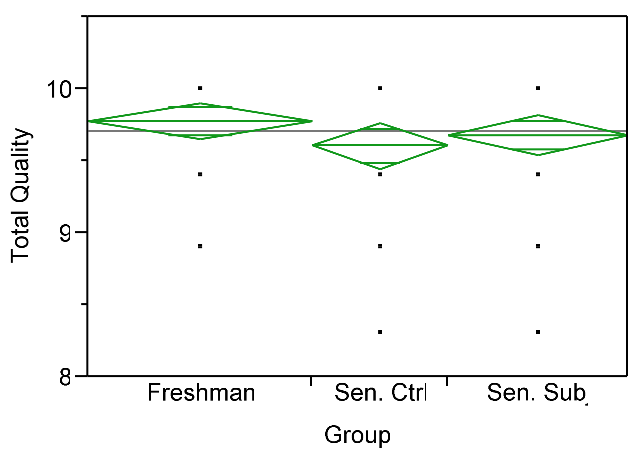

Figure 16: Total Quality for All Groups

Next we ran a student's t-test of the quality results, as shown in Figure 16. All groups received average scores greater than 9 for quality, which shows that all groups have developed a set of concepts that are generally feasible for production. The mean scores for the freshmen group, senior control group, and senior subject group were 9.78, 9.60 and 9.68, respectively. At an alpha value of 0.1 there is no statistically significant difference between any pair of groups.

Further, looking at the design fixation metric for all three groups, the results show how the senior level students, independent of the defixation instructions given, designed concepts that, on average, had roughly 70% of the same features as the past product. The remaining 30% (i.e., the non-conforming features) were mainly add-on functions. Add-on functions, while just one possible route to innovation, can result in innovative products[32]. Interestingly, the freshman students created significantly ($p<0.09$) less conforming concepts, again hinting that the senior-level students exhibited more limited design thinking. The student t-test gives the means of fixation to be 6.83, 6.73, and 6.29 for the senior control, senior subject and freshmen respectively. At an alpha level of 0.1 there was a significant difference between the freshman control and both senior groups.

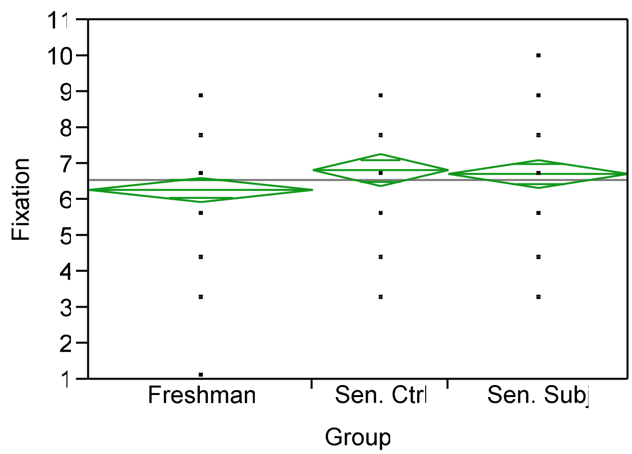

Figure 17: Conformity (Fixation) for All Groups

Discussion of Results

The novelty metric showed a significant difference in the level of creativity and innovation of the freshmen relative to the seniors. Even the defixated seniors were unable to compete with the creative alarm clock concepts developed by the freshmen. This result suggests that age or educational level may influence creative thinking. It may be important to make changes to the typical engineering curriculum to further develop the creative abilities of freshman students and to nurture that creativity throughout the engineering curriculum. Senior students seem to be more fixated on what they know for certain when developing the concepts instead of the potential improvements and changes that could be explored.

The quality metric showed that all three groups developed concepts of similar quality and feasibility at the overall concept level. At the basic feature level, there were some differences in the scores, but the average for each group was greater than nine (on a scale of zero to ten), indicating that all of the designs were technically feasible.

The fixation metric was used to measure the conformity of generated concepts to the sample clocks used in the experiment. Although all of the groups scored between six and seven, on average, for conformity, only the freshman group exhibited a significantly lower conformity score than the other groups. Students conform to some features more than others, with innovative, non-conforming solutions appearing most frequently for features such as mode of alarm, display type, alternative functions, and shape/layout.

In addition to the concept generation methods used in this study, there are also several methods that may be used to select concepts based on appropriateness or customer requirements.[18, 28, 31] Although these concept selection methods help to find concepts that satisfy customer needs, they also tend to select ordinary concepts due to the neglect of "product superiority" as a criterion.[9] The selection of concepts on pure appropriateness inhibits a move towards innovation.

Conclusions

The results of this concept generation study support the conclusion that freshman engineering students are more innovative than their senior-level counterparts. Freshman groups consistently scored higher on novelty metrics without sacrificing quality and feasibility from a manufacturing and design perspective. Also, the freshman group proved to be most capable of thinking beyond the sample clocks given to them in the study. Additional experiments would be very helpful not only for increasing the sample size but also for isolating the effects of age, major, institution, and curriculum on the results. Pending further studies, the results of this preliminary study imply that students become less creative as they progress through the engineering curriculum. Engineering curricula may need to be revisited to bolster students' creative abilities over the four years of undergraduate engineering education.

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