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An Experimental Investigation of the Innovation Capabilities of Undergraduate Engineering Students

NICOLE GENCO, KATJA HÖLTTÄ-OTTO, AND CAROLYN CONNER SEEPERSAD[a]
University of Massachusetts, Dartmouth, The University of Texas at Austin[a]

BACKGROUND
One of the goals of most undergraduate engineering curricula is to prepare students to solve open-ended design problems. Solving design problems requires applying technical knowledge to create original ideas and turn those into practical applications. However, the impact of engineering curricula on the innovation capabilities of undergraduate engineers is not well understood.

PURPOSE (HYPOTHESIS)
This study seeks to provide insights into the research question of whether freshman undergraduate engineering students can be more innovative than seniors. Innovation is measured in terms of the originality of the solutions they propose for an open-ended design problem, as well as the technical feasibility of those solutions for practical application.

DESIGN/METHOD
Freshman- and senior-level undergraduate engineering students were tasked with developing solutions to a specific design problem (a next-generation alarm clock). Both levels of students used a modified 6-3-5/C-sketch method for generating concepts. A fraction of both the freshman and the senior students also received innovation enhancement. Resulting concepts were analyzed for originality and technical feasibility.

RESULTS
Freshman students generated concepts that were significantly more original than those of seniors, with no significant difference in quality or technical feasibility of the concepts generated by the two levels of students.

CONCLUSIONS
Within the limitations of the study, the findings suggest that freshman engineering students can be more innovative than their senior-level counterparts. This motivates the need for additional studies to investigate the effect of factors such as skill acquisition and design curricula on the innovation capabilities of students.

KEYWORDS
creativity, innovation

INTRODUCTION

Dr. Charles Vest, the President of the National Academy of Engineering, eloquently summarized the importance of innovation to America's competitiveness in the global marketplace: "...innovation is the only mechanism that can actually change things in substantive ways. Innovation is where creative thinking and practical know-how meet to do new things in new ways, and old things in new ways (Friedman, 2008)." To be competitive in modern contexts, engineers are challenged with the task of creating innovative products (ASME Council on Education, 2004; Council on Competitiveness, 2005; Duderstadt, 2008), and engineering curricula are challenged to enhance students' innovation capabilities.

Despite its prominence on the national agenda, "innovation" tends to be a very general term that means very different things in different contexts. In this proposal, "innovation" is defined as a specific class of solutions to open-ended engineering design problems. Innovative solutions must be both original (or creative) and practically applicable. While creativity is defined as the ability to generate original solutions to engineering design problems, innovation is the application of those solutions to useful or practical purposes in ways that are technologically and economically feasible (Amabile,Conti, Coon, Lazenby, & Herron, 1996). In related work, the authors have studied nearly 300 award-winning innovative products and identified some of the characteristics that contribute to innovation, including creative changes in functionality, architecture, and product-user interactions (Saunders, Seepersad, & Holtta-Otto, 2009, 2011).

As evidenced by the imminent failure of the majority of products introduced to the marketplace (Cooper, 2005) and the abundance of grand engineering challenges (National Academy of Engineering, 2008), innovation is difficult to achieve, and it can be difficult to teach as well. A variety of factors can influence the innovation capabilities of engineering students, many of them for the worse. One of the most significant barriers to innovation is design fixation. Design fixation is defined as an unintentional adherence to a set of ideas or concepts limiting the output of conceptual design (Jansson & Smith, 1991). Researchers in cognitive science and engineering design have found that both engineering design students and practicing engineers generate concepts very similar to those with which they are familiar, whether familiarity is caused by previous experience or by recent exposure to potential solutions (Christiansen & Schunn, 2007; Chrysikou & Weisberg, 2005; Jansson & Smith, 1991; Kolodner & Wills, 1996; Linsey, Tseng, Fu, Cagan, & Wood, 2010; Nijstad, Stroebe, & Lodewijk, 2002; Perttula & Sipila, 2007; Purcell & Gero, 1996; Purcell, Williams, & Gero, 1993; Smith, Ward, & Schumacher, 1993).

Given that most engineers are exposed to a plethora of existing engineered products or systems, the prevalence of design fixation is a significant concern because it indicates that engineers may find it difficult to generate original or creative solutions. The fixation persists throughout the design process and designers are likely to stick to their original solution and not consider potentially better alternatives (Kershaw, Hölttä-Otto, & Lee, 2011). Related engineering education research heightens the level of concern. For example, Condoor, Shankar, Brock, Burger, & Jansson (1992) found that engineering students are often hampered by design fixation and a lack of generation of alternative solutions, among other factors. The potential impact of overcoming design fixation was documented in a study of freshman versus senior engineering students, in which Atman, Chimka, Bursic, & Nachtmann (1999) found that senior students who generated a greater number of alternative concepts produced final designs of significantly higher quality.

While the knowledge and skills acquired by students in their undergraduate engineering courses help them assess and enhance the feasibility of design solutions, *skill acquisition alone does not necessarily enhance creativity or reduce design fixation.* For example, Guilford (1967) 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, those with high levels of intelligence and skill showed a wide range of creative output, from lack of creativity to high levels of creativity. Similarly, other researchers have suggested that highly skilled individuals may have trouble adapting their thinking to produce creative work (Ericsson, 1999; Weisberg, 1993). As engineering students gain knowledge and design skills, it is assumed that they go through a normal process of cognitive skill acquisition (Fitts & Posner, 1967). Most theories of skill acquisition state that the culmination of skilled practice involves the automatic application of knowledge, rules, and decisions (Anderson, 1983). As has been shown in cognitive psychology research, automatic application of knowledge can backfire when a method that previously worked now fails (Luchins, 1942) or when previous experience is not applicable to a new situation (Hecht & Proffitt, 1995). Repetition of a particular pattern of responses leads to increased errors in new situations (Besnard & Cacitti, 2005), particularly in individuals with greater levels of knowledge (Woltz, Gardner, & Bell, 2000). Repetition and automatic application or adherence to a set of previously conceived ideas is closely related to design fixation, and these studies suggest that the tendency to fixate could increase with skill acquisition throughout the undergraduate engineering curriculum.

With several factors potentially hindering their capacity to be creative and innovative, the impact of undergraduate engineering education on the innovation capabilities of undergraduate engineers is unclear. Atman et al. (1999) used verbal protocol analysis to study how freshman and senior engineering students solve an open-ended design problem. They found that senior students (at a single institution) generated slightly higher quality designs and that quality was correlated with the number of concepts considered by the students. Cross, Christiaans, and Dorst (1994) compared second and final year engineering student performance on a design problem and found that the final year students produced more creative solutions. Ball, Evans, Dennis, and Ormerod (1997) found that practicing senior engineers considered several design solutions before choosing one, while junior engineers tended to commit to one solution early in the design process. In contrast, there is conflicting evidence to suggest that freshman students may be better equipped to solve ill-defined problems using creative thinking than senior-level engineering students (Lai, Roan, Greenberg, & Yang, 2008). Another study suggests that engineering and non-engineering freshmen are equally creative in terms of general creativity as measured by creative personality, creative temperament, and cognitive risk tolerance (Charyton & Merrill, 2009).

In this research, the authors pose the question of whether freshman engineering students are more innovative than seniors, in terms of the originality and quality or technical feasibility of the solutions they generate for open-ended design problems. A concept generation experiment is designed and implemented to answer the question, and results are analyzed. Before discussing the details of the study, it is important to review some of the methods that have been devised for enhancing design innovation and the metrics that have been introduced for measuring innovative outcomes.

Methods for Enhancing and Measuring Innovation Capabilities

Methods for Enhancing Innovation Capabilities

Educators and researchers have made many efforts to infuse creativity and other skills for solving open-ended design problems in undergraduate engineering education, ranging in scope from curriculum reform to learning modules for individual courses. Dym, Agogino, Eris, Frey, and Leifer (2005) reviewed the history and role of design in engineering curricula, including the progression of senior design (capstone) courses and the introduction of freshman design (cornerstone) courses in the 1990s. For example, MIT implemented a CDIO (Conceive Design Implement Operate) curriculum to educate students who are capable of creating and building engineering systems (Crawley, Malmqvist, Ostlund, & Brodeur, 2007). Other recent developments include Northwestern's introduction of a special first year course and some intermediate level courses as part of their Design Institute to better integrate design into their curriculum (Hirsch et al., 2001; Colgate, McKenna, & Ankenman, 2004). Carnegie Mellon University (Ambrose & Amon, 1997), Villanova (Clayton, Radlinksa, & Wojcik, 2010), and the University of Massachusetts, Dartmouth (Pendergrass et al., 2001) have also described first-year design courses. Although one or more courses in most engineering curricula typically involve solving open ended design problems, often there is still a lack of emphasis on developing the creativity and innovation capabilities of engineering students, despite several requests for incorporating this objective into engineering curricula (Angelo & Cross, 1993; McKenzie, Trevisan, Davis, & Beyerlein, 2004).

Creativity, as part of the engineering design curriculum, is typically taught by introducing a set of ideation methods as part of a junior- or senior-level, or occasionally a freshman-level design class. Several formal concept generation or ideation methods have been proposed including brainstorming (Osborn, 1963), brainwriting (Geschka, Schaude, & Schlicksupp, 1973), 6-3-5 (Rohrbach, 1969; Pahl & Beitz, 1996) or C-sketch (Shah, 1998), and TIPS or TRIZ (Altshuller, 1984). For example, in the 6-3-5 method, 6 people individually generate 3 ideas and record them as phrases on a sheet of paper (Rohrbach, 1969; Pahl & Beitz, 1996). Otto and Wood (2001) suggest a variation on 6-3-5 in which sketches and phrases are circulated-a technique that is similar to C-sketch (Shah, 1998). The Theory of Inventive Problem Solving (TIPS or TRIZ) is based on a comprehensive study of patent claims by Altschuller and colleagues (Altshuller, 1984), resulting in a set of principles for alleviating design conflicts. In addition to these common techniques, several concept generation methods have been formalized more recently, including Design by Analogy (Linsey et al., 2006, 2008) and Biomimetic Concept Generation (Chiu & Shu, 2007).

Multiple studies compare ideation methods to evaluate their effectiveness in an engineering design context. For example, Mullen, Johnson, and Salas. (1991) 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 (Paulus & Yang, 2000), a significantly higher quantity of unique ideas is found when designers exchange ideas rather than work alone. Shah et al. (1998; 2000) analyzed three ideation methods: 6-3-5, C-Sketch, and the Gallery method. In the Gallery method, designers sketch concepts individually, post the sketches for the group to view, and discuss and then repeat the process. 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. Shah et al., (1998; 2000) found that C-Sketch was superior to the other two methods in terms of the quality, novelty, and variety of ideas generated. Linsey (2007) confirmed the conclusion of Shah et al. (2000) 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, Kuhr, Wang, Crawford, and Wood (2009) tested a modified 6-3-5/C-sketch method which 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 (Otto & Wood, 2001). Weaver et al. (2009) showed that combining the modified 6-3-5/C-sketch method with pre-concept generation innovation enhancement exercises can further improve the outcome. In summary, the evidence supports the use of the modified 6-3-5/C-sketch method suggested by Otto and Wood (2001); accordingly, it is used to scaffold the design process in this research study, as described in Section 3.

Methods for Measuring Innovation Capability

There are many ways to evaluate innovation, including *indirect* measures of innovation capabilities via metrics focused on the innovation process and/or the individual's creative personality and *direct* measures based on the outcomes of the design innovation process. For example, surveys, questionnaires, concept maps, interviews, observations, grades, and archival demographic data have all been proposed as methods for evaluating design capabilities (Atman et al., 2000). There is conflicting evidence regarding how well some of these methods correlate with measures of design outcomes. For example, Adams, Punnakanta, Atman, and Lewis (2002) found that reflective essays written by students correlated poorly with measures of actual design performance. On the other hand, there is some evidence that self-efficacy, or belief in one's own abilities toward a given task (Bandura, 1997), is a reliable predictor of design outcomes since confidence levels may limit a designer's scope or creativity (Bandura, 1997). Self-efficacy in engineering can be divided into subareas including design (Carberry, Lee, & Ohland, 2010) and creative self-efficacy (Tierney & Farmer, 2002;Karwowski, 2010;Beghetto, Kaufman, & Baxter, 2011), and surveys have been developed to measure self-efficacy in those domains (Beghetto et al., 2011; Carberry et al., 2010; Tierney & Farmer, 2002).

In addition to reflective essays, self-efficacy, and other techniques for indirect assessment of innovation capabilities, one could measure the creative personality of an individual, versus directly measuring the creative outcome that the person produces (Charyton, Jagacinski, & Merrill, 2008; Ekstron, French, Harman, & Dermen, 1976). In engineering, the outcome tends to be of greater interest, assuming the engineers' job is to realize products and systems that are effective and useful. Furthermore, measures of creative personality and creative outcomes are not necessarily correlated (Charyton & Merrill, 2009), making it difficult to rely on personality measures when outcomes are of greater interest.

In engineering design research, metrics have been established for evaluating the outcomes of concept generation or ideation processes. Shah et al. (2000; 2003) have proposed metrics for quality, quantity, novelty, and variety of solutions. For each metric, Shah et al. (2000; 2003) decompose a design into its constituent functional components, evaluate the quality/quantity/novelty/variety of solutions for each function, and then combine the ratings into an overall metric via a weighted sum formulation. To avoid the subjectivity of the weighting system, Linsey and colleagues (2006, 2007, 2008) develop their own set of metrics for quality, quantity, novelty, and variety. Quantity, for example, is measured by counting the number of items that satisfy one or more of the functions of the component, as defined by the common basis functions (Stone & Wood, 2000). Charyton and colleagues (2008, 2009) propose instruments for measuring the fluency, flexibility, and originality of creative outcomes. Whereas Shah et al.'s novelty metric is designed to compare each concept to a set (or universe) of predefined solutions, such as the other concepts generated by the same experiments, *Charyton's originality metric* provides an explicit scale for rating each feature. Accordingly, Charyton's originality metric is more useful for measuring innovation relative to the competing marketplace, and it is modified for use in this research study, as described in Section 3.

RESEARCH METHOD

In this research study, an experiment is designed and implemented to evaluate the innovation capabilities of both freshman and senior-level undergraduate engineering students. The experiment is summarized in Figure 1. As shown in the figure, the independent variables include the class rank of the participants and the solution of a design task with or without innovation enhancement strategies. Freshman students are classified as those enrolled in first-year engineering courses, while seniors are defined as those involved in final-year design courses. Each participant is tasked with solving a fixed design problem with a modified 6-3-5 ideation technique. Some students are exposed to innovation enhancement exercises prior to the implementation of the modified 6-3-5 method; others are not. In all cases, the students are subject to identical design tasks and experimental protocol, including identical statements of the design tasks, ideation times, and group sizes (either 4 or 6 participants per group). Noise factors, which were not controlled in this study, include student demographics (GPA, gender, etc.) and prior experience levels (internships, special skills, etc.). Details of the experiment are provided in the rest of this section.

Participants

Ninety-four undergraduate mechanical engineering students participated in the study at the University of Massachusetts, Dartmouth over the course of three semesters. Forty-eight freshman students were enrolled in required introductory courses on applications of mechanical engineering as a part of the university's IMPULSE (Pendergrass et al., 2001) program, and forty-six senior students were enrolled in capstone design courses. The students at each rank were divided into two categories: one category of participants was subjected to innovation enhancement techniques prior to the modified 6-3-5 ideation process and the other category of participants was not. The two categories are differentiated with the labels *innovation enhancement* and *non-enhancement*, respectively. There were 20 and 28 students in the freshman innovation enhancement and non-enhancement categories, respectively, and 28 and 18 students in the senior innovation enhancement and

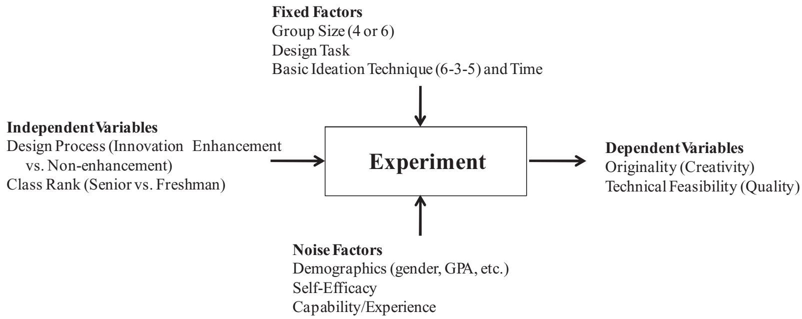

FIGURE 1. P-diagram for experiment design.

non-enhancement categories, respectively. Each innovation enhancement and non-enhancement set of participants was subdivided into ideation groups of either four or six students. The ideation group size was later shown to have no statistically significant effect on the results of the experiments.

Experimental Procedure

Each ideation group was presented with the following open-ended design problem:

> Thank you for helping with our study. We are trying to design the next generation of breakthrough alarm clocks and request your help in generating ideas. We have provided 2 standard alarm clocks with which you can interact to improve your understanding of potential improvements and customer needs. You will be working in pairs, taking turns interacting with the alarm clocks. You will have 30 minutes to interact with the alarm clocks followed by a round of modified 6-3-5 concept generation. Before we begin are there any questions?

The non-enhancement groups interacted freely and spontaneously with the alarm clocks. The innovation enhancement groups were given an additional prompt:

> You are given different disabling devices to make the interaction with the clocks more challenging. Please operate the clocks with oven mitts, earmuffs and blindfolds. Make sure you use all 3 disabling devices in the 30 minutes provided for interacting with the clocks. Also make observations of your partner as he/she uses the clocks with the disabling devices.

This additional prompt is motivated by the Empathic Experience Design method under development by the authors (Genco, Hölttä-Otto, & Seepersad, 2011). Empathic creativity techniques are designed to heighten users' awareness of their interactions with a product by challenging or disabling those interactions in meaningful ways (Genco, Hölttä-Otto, & Seepersad, 2010; Genco et al., 2011; Green, Seepersad, & Hölttä-Otto, 2010; Hannukainen & Hölttä-Otto, 2006). In this experiment the disabling devices included blindfolds to simulate dark conditions, ear plugs with ear muffs to simulate deep sleep, and oven mitts to simulate limited dexterity associated with physical challenges (such as arthritis or unusually large fingers) or periods of limited consciousness after a deep sleep. The intent is to help participants experience the limitations of existing products, expand their awareness beyond the features of those products, and open their minds to more alternative concepts. While interacting with the alarm clocks, students in each ideation group were encouraged to work together and discuss the products. Each ideation group was allotted up to 30 minutes of interaction with the alarm clocks. The allocated interaction time was judged to be sufficient because the innovation enhancement and non-enhancement groups were observed to stop interacting with the clocks after approximately 20-25 minutes and 15 minutes, respectively.

After each ideation group interacted with the clocks, they immediately moved on to the concept generation phase of the activity. Each group used the modified 6-3-5 method to generate concepts for the design of a "next generation of breakthrough alarm clocks." The 6-3-5 method requires "6" participants to develop "3" concepts per person, in the form of sketches with labels. Students were allocated 15 minutes to develop these 3 concepts. The allocated time was judged to be sufficient because most students were observed to complete their concepts before the 15 minutes expired. Every 5 minutes, students were reminded of the time remaining until the 15 minutes had passed. Then, students passed their concepts clockwise to their nearest neighbors, and five minutes were allotted for modification of the original concepts. Students were asked to quickly review each concept to gain an understanding of the underlying intention and then to add any additional modifications or enhancements to the concept. The clockwise rotation continued, every 5 minutes, until the concepts were returned to their original authors. For groups of six participants, five rotations were performed, resulting in a 6-3-5 method (6 students, 3 concepts per student, 5 rotations); for groups of four participants, only three rotations were performed, resulting in a 4-3-3 method. During the 6-3-5 method, talking was prohibited.

Data Analysis and Metrics

Since the focus of the study is on measuring the innovation capabilities of the students, the concepts were analyzed for two components of innovation-originality and technical feasibility-using a modified version of Charyton's originality metric (2008; 2009) and a modified version of Shah's quality metric (2000, 2003), respectively.

Originality was measured using the five-point scale defined in Table 1. The scale is derived from an eleven-point scale used by Charyton et al. (2008) for measuring originality, as illustrated in Table 3. Repeatability studies performed by the authors and other researchers indicate that scales with fewer intervals improve the repeatability of the results (Friedman & Amoo, 1999; Srivathsavai, Genco, Hölttä-Otto, & Seepersad, 2010). The authors also found the 11-point scale more difficult to use because the words do not have an intuitive ranking with respect to the level of innovation (e.g., why is "exceptional" ranked higher than "insightful" but lower than "valuable to the field?"). Additionally, the five-point scale aligns with commonly applied five-point Likert scales, one of the most recommended scales for use in rating systems (Friedman & Amoo, 1999).

Rather than measuring the originality of an overall concept, originality was measured at the feature level. Feature level analysis facilitates accounting for multiple innovative aspects of a design and helps promote consistency and repeatability between concepts and evaluators (Srivathsavai et al., 2010). Features were defined according to Table 2, and a list of standard elements for each feature was compiled by examining alarm clocks found at common retail and online stores, such as Target, Walmart, and Amazon.com. For each feature, originality was evaluated by comparing the features of the concept design to the list of standard elements. After all of the features were evaluated for a concept, the

TABLE 1
Five-point Originality Metric

Score	**Description**
0	Common
2.5	Somewhat interesting
5	Interesting
7.5	Very interesting
10	Innovative

TABLE 2
Basic and Additional Features of an Alarm ClockMetric

Basic Features	Additional Features
Mode of alarm	Music
Display type	Alternative use
Information shown	Shape/Layout
Mode of input	
Snooze	
Energy source	

maximum feature-level score was identified and assigned to each concept as its overall originality score. The rationale is that a concept can only be as innovative as its most innovative idea.

Using the same set of features, the concepts were analyzed for technical feasibility with a quality metric introduced by Shah et al. (2003) and modified by Linsey (2007), as illustrated in the flowchart in Figure 2. According to the flowchart, all existing solutions receive a score of 10. Solutions that do not exist, but are not likely to be technically difficult (e.g., solutions that can be borrowed from other types of products) receive a score of 7. If the solution is likely to be technically difficult (but feasible) or completely infeasible, it receives a score of 4 or 0, respectively. A watch alarm, for example, would score a ten for feasibility because it already exists. An alarm that wakes the user by REM sleep patterns would score a four because it is technically feasible but likely to be technically difficult, given the need to translate laboratory sensors and monitoring equipment into a compact, mass-produced device.

The quality metric was applied to each feature for each concept. Since a concept is likely to be as feasible as its least feasible feature, the minimum feature-level quality score for each component was tabulated as a means of analyzing the results.

TABLE 3
Eleven-point Originality Metric

Score	Description	Score	Description
0	Dull	6	Insightful
1	Common	7	Exceptional
2	Somewhat interesting	8	Valuable to the field
3	Interesting	9	Innovative
4	Very interesting	10	Genius
5	Unique and different		

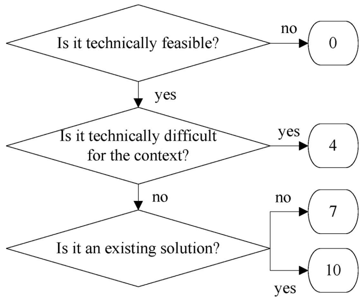

FIGURE 2. Flowchart for analyzing concept quality.

To further illustrate the metrics, they are applied to the concepts illustrated in Figures 3 through 6. The first concept (Figure 3) was designed by a freshman innovation enhancement group. The ear plug concept is unique in shape, placement, and mode of alarm. It wakes the user through subtle waves that could only be heard by the user and would not disturb another person sleeping in the room. It also comes with a charging unit where the user sets the alarm.

The next clock concept, shown in Figure 4, is a sample from a senior innovation enhancement group. The concept is a projector/alarm clock combination. It displays video on a screen in the user's bedroom. It responds to inputs from a remote control as well as human motion. It hangs from the ceiling, and it is wired into the home electrical system to receive electricity. Alarm clocks that project the time on a wall or ceiling are common in the marketplace, but video projection is not a common feature in existing alarm clocks, nor is motion sensing.

Figure 5 is a sample concept from a freshman non-enhancement group. It is a moving alarm clock that must be chased by the user. When the alarm sounds, the ball rolls off the base, requiring the user to retrieve the ball in order to shut it off. It comes with a

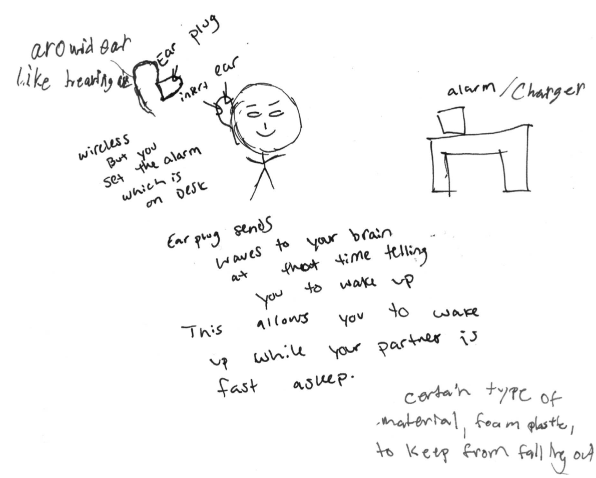

FIGURE 3. Sample concept from a freshman innovation enhancement group.

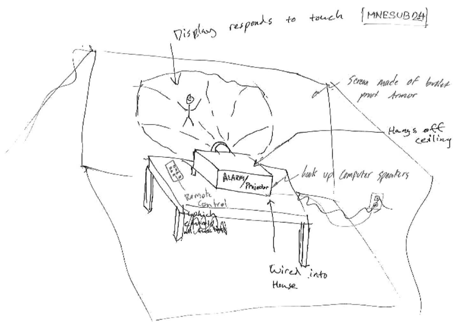

FIGURE 4. Sample concept from a senior innovation enhancement group.

rechargeable station and has the ability to play radio or personal songs via a memory card. The moving alarm clock is interesting, but it is similar to other moving or rolling alarm clocks available from prominent retailers.

The clock in Figure 6 was developed by one of the senior non-enhancement groups. This clock is both digital and analog. It allows the user to choose from multiple alarm sounds and comes equipped with a snooze option located on top of the alarm clock. It has a dim backlight to help the user read the time at night, a standard feature for most alarm clocks. It has a standard electrical cord as well as backup batteries, which are also standard features for most alarm clocks. Although this clock seems to possess all desired functions of an alarm clock, it has no major features that distinguish it from the alarm clocks commonly available in the marketplace.

The features of the sample alarm clock concepts are outlined in Table 4. In Table 4, 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 to alarm clocks that are commonly available in retail stores.

After features are analyzed, originality scores are calculated for each concept. Table 5 displays the originality scores for each feature, as well as the total novelty and basic novelty score for each concept. The originality score for each concept is calculated using the 5-point scale previously described in Table 1. The rater assesses each clock feature and gives it a score of either 0, 2.5, 5, 7.5, or 10, in comparison with the features of other clocks in the concept pool as well as clocks that are commonly available in the market

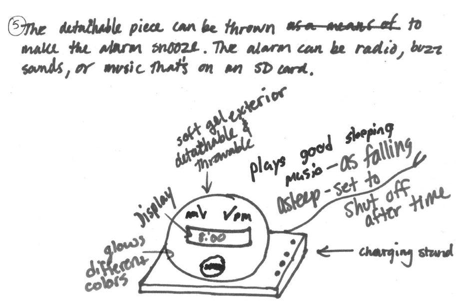

FIGURE 5. Sample concept from a freshman non-enhancement group.

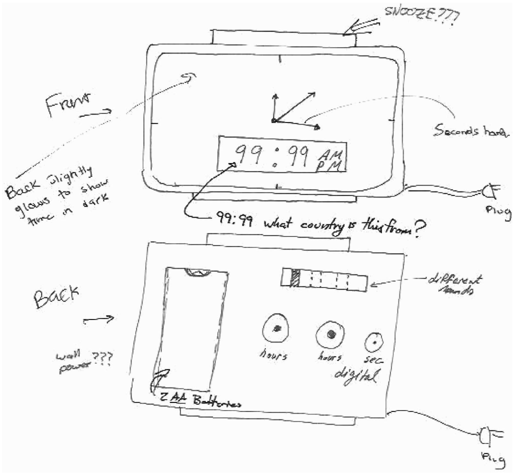

FIGURE 6. Sample concept from a senior non-enhancement group.

TABLE 4
Features of Sample Concepts

	Freshman Innovation Enhancement Concept	Senior Innovation Enhancement Concept	Freshman Non-enhancement Concept	Senior Non-enhancement Concept
Basic Features				
Mode of Alarm	Waves	Standard	Lights	Multi Sound
Display Type	Standard	Projector	Standard	Standard
Information Shown	Standard	Standard	Standard	Standard
Mode of Input	Separate Unit	Remote/Motion	Standard	Standard
Energy Source	Rechargeable	Standard	Rechargeable	Standard
Snooze	None	None	Throw	Standard
Additional Features				
Music	Standard	Standard	Combo	Standard
Alternative Use	Standard	Projector	Standard	Standard
Shape/Layout	Earbud	Ceiling	Ball/Base	Standard

place. For example, the mode of input for the senior innovation enhancement alarm receives a score of 7.5 (very interesting) because the projected display is intended to respond to user motion and touch. Other features of the alarm, such as the ceiling mount and projector display are also unusual, earning a score of 5 (interesting). Standard

TABLE 5
Originality Scores for Sample Concepts

	Freshman Innovation Enhancement Concept	Senior Innovation Enhancement Concept	Freshman Non-enhancement Concept	Senior Non-enhancement Concept
Basic Features:				
Mode of Alarm	10	0	2.5	0
Display Type	0	0	0	0
Information Shown	0	0	0	0
Mode of Input	2.5	7.5	0	0
Energy Source	2.5	0	2.5	0
Snooze	0	0	5	0
Additional Features:				
Music	0	0	0	0
Alternative Use	0	5	0	0
Shape/Layout	5	5	5	0
Scores:				
Maximum Originality	10	7.5	5	0

features automatically earn a score of 0 (common) because they already exist on commonly available alarm clocks.

Table 3 tabulates the quality scores for each of the concepts. Most of the features received scores of 10, which indicates that these features are technically feasible and are not technically difficult for the context. One exception is the mode of input for the senior innovation enhancement group's concept, which received a quality score of 7. Although motion and touch sensors do exist and are therefore technically feasible, they are not commonly available in alarm clocks, requiring some engineering integration.

Data Coding and Reliability

To investigate the repeatability of the analysis, a subset of concepts was evaluated independently by two members of the research team. The inter-rater reliability between the two researchers was found to be very good for the originality metric with a Cohen's Weighted Kappa value of 0.67 and a Spearman Coefficient of 0.66. The inter-rater reliability was found to be excellent for quality, with a weighted Kappa value greater than 0.9 and a Spearman Coefficient of 0.57. Cohen's Weighted Kappa (1968) is a nominal scale agreement measure that accounts for chance agreement and includes a provision for scaled disagreement (e.g., a disagreement of 7.5 versus 10 is not penalized as severely as a disagreement of 2.5 versus 10). Values of 0.7 (on a scale in which 0 represents chance agreement and 1.0 represents perfect agreement) are considered excellent agreement for Cohen's Weighted Kappa and Cohen's Kappa.

TABLE 6
Quality Scores for Sample Concepts

	Freshman Innovation Enhancement Concept	Senior Innovation Enhancement Concept	Freshman Non-enhancement Concept	Senior Non-enhancement Concept
Basic Features:				
Mode of Alarm	7	10	10	10
Display Type	10	10	10	10
Information Shown	10	10	10	10
Mode of Input	10	7	10	10
Energy Source	10	10	10	10
Snooze	10	10	10	10
Additional Features:				
Music	10	10	10	10
Alternative Use	10	10	10	10
Shape/Layout	10	10	10	10
Scores:				
Minimum Quality	7	7	10	10

RESULTS

All of the concepts were analyzed in terms of maximum originality and minimum quality scores. A maximum originality score was obtained for each concept by rating the originality of each of the concept's features, as illustrated in Table 5 for sample concepts, and then recording the maximum originality score among all of the concept's features. Similarly, a minimum quality score was obtained by identifying the minimum quality score among all of the concept's features. Compiled results are reported in Figures 7 and 8 for each of the participant categories. One-way ANOVA was used to compare results between categories, and the results are illustrated as diamond plots. The line in the center of each diamond represents the mean for each category, 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. If the range defined by the overlap marks overlaps with that of another category, then the difference between the means of the two categories of participants is not statistically significant at a 95% confidence level.

As shown in Figure 7, the freshman innovation enhancement groups earned significantly higher maximum originality scores than any of the other categories, followed by the senior innovation enhancement and freshman non-enhancement groups, which earned equivalent scores. The senior non-enhancement groups earned the lowest originality scores. The mean maximum originality scores for the freshman innovation enhancement, senior innovation enhancement, freshman non-enhancement, and senior non-enhancement groups were 5.24, 4.48, 4.42, and 3.30, respectively. The freshman

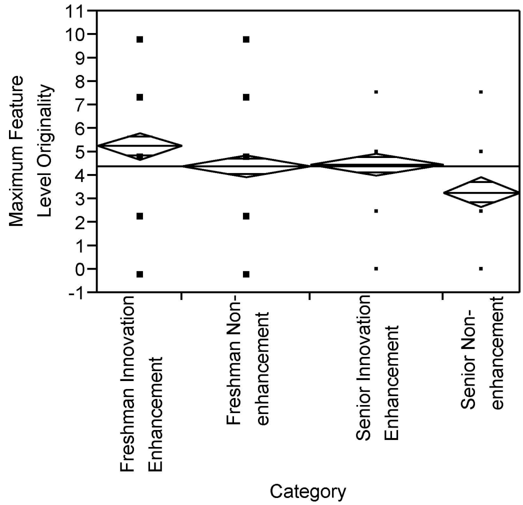

FIGURE 7. Maximum originality per category.

innovation enhancement groups' concepts were significantly more original that those of the senior innovation enhancement groups (*p*-value of .0418), freshman non-enhancement groups (*p*-value of .0310), and senior non-enhancement groups (*p*-value of less than .0001). No statistically significant difference was observed between the senior innovation enhancement groups and the freshman non-enhancement groups (*p*-value of .8758); however, the senior innovation enhancement groups performed significantly better than the senior non-enhancement groups (*p*-value of .0025).

As shown in Figure 8, the senior-level groups produced concepts with slightly higher minimum quality scores than those of the freshman groups, but the differences were not statistically significant. All groups received average quality scores greater than seven (on a scale of 0-10), which indicates that all groups developed concepts that were generally feasible for production. The mean scores for the freshman innovation enhancement, senior innovation enhancement, freshman non-enhancement, and senior non-enhancement groups were 8.03, 8.44, 7.91, 8.60, respectively, with no statistically significant difference between the scores for an alpha value of 0.1.

DISCUSSION OF RESULTS

As expected, most concepts mimic the features of alarm clocks the students have been exposed to illustrating the prominence of design fixation. We do find that an innovation enhancement method increases originality, but interestingly the originality metric showed a significant difference in the level of creativity of the concepts produced by the freshmen relative to the seniors. Even the seniors whose performance was improved by use of an innovation enhancement method were only able to obtain the same level of originality scores as the freshmen groups who did not use the innovation enhancement method.

The differences in creativity were further evident in the concepts produced by the students. All participants interacted with prototype products prior to ideation. While the freshmen (correctly) used those interactions to focus on the idea itself and its overall

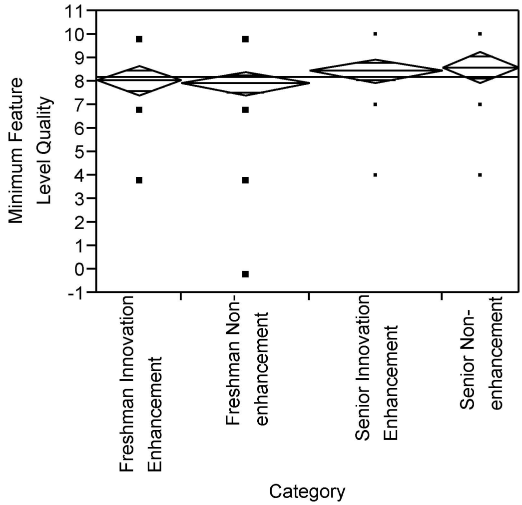

FIGURE 8. Minimum quality per category.

functionality, the seniors borrowed various technical details from the prototypes that did not lead to innovation. In general, senior students clearly used engineering skills and knowledge acquired from their undergraduate courses; when generating concepts, they seemed to be more fixated on creating feasible designs with high levels of certainty, rather than exploring a variety of potential improvements and changes to existing designs. Moreover, senior students seemed to focus highly on procedural skills gained during their engineering education, specifically, technical drawing. Their drawings often included different projections of the concept and relatively high levels of detail on potential attachments between modules and other engineering details. These characteristics are illustrated in the sample concepts in Figure 9.

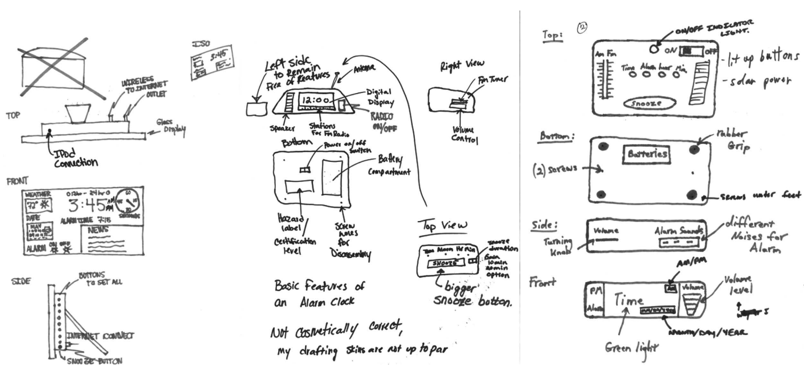

Figure 9. Sample senior-level concepts (technical drawing focus).

Since innovation is rooted in a combination of both creativity and usability (Amabile et al. 1996), a quality metric was used to assess the feasibility and ease with which the concepts could be implemented. Although the senior-level concept were often more detailed than the freshman-level concepts, the quality metric indicated no statistically significant differences in the quality of the concepts generated by the freshman-level groups versus the senior-level groups.

Conclusions

The results of this study demonstrate that freshman-level engineering students can develop more innovative concepts than senior-level mechanical engineering students. Specifically, at the University of Massachusetts, Dartmouth, freshman-level students generate designs with higher levels of originality than their senior-level counterparts, without sacrificing technical feasibility from a manufacturing and design perspective.

The results of this study suggest that students do not necessarily become more creative as they progress through a mechanical engineering curriculum, although they may acquire many other types of engineering skills and knowledge. For example, senior-level students obviously used drafting skills and considered technical details such as material choices and sensor selections that were not prominently displayed in freshman-level concepts. These characteristics are evidence of skill acquisition during the undergraduate engineering curriculum (Anderson, 1983). Although the level of detail was higher for the senior-level concepts, the overall technical feasibility, or likelihood of successfully manufacturing, of their concepts was not significantly higher than the freshman-level students; perhaps, partially because the design problem was not especially novel or technically challenging.

Additional research should be conducted to further pinpoint the exact effects of factors such as age, major, motivation, previous experience, and curriculum on the results. For example, further research should repeat this study at different universities with different curricula (e.g., with and without project-based curricula), to better understand whether the curriculum influences the innovation capabilities of graduating students, and if so, whether specific types of classes and pedagogical techniques tend to enhance those capabilities more than others. Depending on the results of these studies, changes to the typical engineering curriculum may be required to nurture and strengthen students' innovation abilities throughout their undergraduate education. Further studies could also explore the effect of age and professional development on innovation capabilities, for example, by comparing freshman and senior undergraduates to advanced graduate students and professional engineers. Longitudinal studies, in which cohorts of students are followed through their engineering curriculum, could also be helpful in assessing the effects of a particular curriculum on groups of students. In addition, factors such as student motivation and self-efficacy could have an effect on their performance on a specific design task, and further research could combine outcome-based metrics with measures of self-efficacy. Finally, it would also be interesting to investigate the effect of the design problem on the results by performing similar studies on an original design problem for which commercially available solutions do not yet exist.

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Authors

Nicole Genco is a graduate student in Mechanical Engineering at the University of Massachusetts, Dartmouth. 285 Old Westport Road, North Dartmouth, MA 02747; u_ngenco@umassd.edu.

Katja Hölttä-Otto is an assistant professor of Mechanical Engineering at the University of Massachusetts, Dartmouth. 285 Old Westport Road, North Dartmouth, MA 02747; katja.holtta-otto@umassd.edu.

Carolyn Conner Seepersad is an assistant professor of Mechanical Engineering at The University of Texas at Austin, 1 University Station, C2200, Austin, TX 78712; ccseepersad@mail.utexas.edu.