Creativity Exercises and Design Methods to Enhance Innovation in Engineering Students

Dr. Michael Lawrence Anderson P.E., United States Air Force Academy

Lt Col Mike Anderson is an Associate Professor and Director of Capstone Programs, Department of Engineering Mechanics, US Air Force Academy. He has pursued research in engineering education for several years in the areas of curriculum design and assessment, capstone design experiences, innovative design methodologies, and enhancing student creativity. In addition, he pursues technical research in autonomous systems, design of terrestrial and aerial robots, flight control of Micro Air Vehicles (MAV), sports science and sports technology. Lt Col Anderson has worked as an F-16 flight control actuation systems engineer and as a Deputy Division Chief in the Air Force Research Laboratory's Munitions Directorate where he led research in GPS-denied navigation for multi-agent autonomous systems. Lt Col Anderson is a registered Professional Engineer and an Associate Fellow of the American Institute for Aeronautics and Astronautics.

Mrs. Karen Elaine Anderson, Destination Imagination Inc.

Karen Anderson graduated from Oregon State University with a degree in Resource Recreation Management and a minor in Youth Agencies. She has been married to Marshall for 49 years and together they have 5 children ranging in age from 45-32. Karen recently retired from the Board of Trustees of Destination Imagination Inc. after 12 years of service but continues volunteering in her home state and at the National Level . Karen has been involved in every aspect of creative problem solving and Destination Imagination Inc. for the past 34 years, for 26 years she was the Affiliate Director of Oregon Destination Imagination Inc and affiliate of the national organization. She has taught numerous classes on creative problem solving, as well as classes to gifted students through a program at Oregon State University. In addition Karen has been a long time volunteer with the Boy Scout receiving the District Award of Merit, Order of the Arrow and other awards. She has served on the Pastoral Council of her Church, chaired the Archdiocese Marriage and Family Life Board, chaired the Corvallis School District Talented and Gifted Advisory Board and was President of Assistance League of Corvallis which serves under privileged youth. She is currently serving on the Leadership Team of The National Assistance League headquartered in Burbank Calif.

Dr. Daniel D. Jensen, Singapore University of Technology and Design/MIT International Design Center

Dr. Dan Jensen retired as a Professor of Engineering Mechanics at the U.S. Air Force Academy in 2018 after 21 years. He received his B.S. (Mechanical Engineering), M.S. (Applied Mechanics) and Ph.D. (Aerospace Engineering Science) from the University of Colorado at Boulder. He has worked for Texas Instruments, Lockheed Martin, NASA, University of the Pacific, Lawrence Berkeley National Lab and MSC Software Corp. His research includes design of Micro Air Vehicles, development of innovative design methodologies and enhancement of engineering education. Dr Jensen has authored over 120 refereed papers and has been awarded over $4.5 million of research grants. He is a Fellow at the Singapore Univ. of Technology and Design's International Design Center.

Creativity exercises to enhance innovation in undergraduate engineering design students

Abstract

This *evidence-based practice* paper describes the use of creativity practice exercises intended to enhance student creativity in a capstone design program. Engineering programs, in general, and capstone design programs, in particular, that seek innovative conceptual solutions to complex problems would benefit from techniques to develop and assess student creativity. Therefore, a study was performed to evaluate two such techniques. Over the first two years of the study, capstone design students in the United States Air Force Academy's Department of Engineering Mechanics were each assigned to one of 14 teams which received various learning experiences (treatments) intended to enhance individual creativity and design project innovation. Twelve of the 14 teams ($n = 70$) received an innovative engineering design curriculum while the control teams ($n = 23$) did not. Six teams ($n = 37$) experienced seven weekly creativity exercises across the fall semester, provided by Destination Imagination, while four teams ($n = 56$) did not. It was expected that the exercises would improve Creativity Index scores in students across the study as measured by the Torrance Tests of Creative Thinking (TTCT) Figural Test. The Creativity Index scores of the students were analyzed using an independent sample t-test to determine if any differences could be detected. Results after the first two years are positive, indicating that students that participated in the creativity enhancing treatments showed higher improvements in Creativity Index scores compared to the controls. However, the statistical significance of these findings are not strong, presumably due to the small sample size. Therefore, the research will continue in subsequent years. In addition, evaluation of the design teams' concepts by experienced engineering design faculty indicated that the teams that participated in the creativity exercises exhibited greater innovation in their design process versus the control. Finally, students reported that the exercises are fun and help them expand their way of thinking to consider unexpected solutions to a diverse array of challenges.

1. Introduction

The capstone design experience is common in Accreditation Board for Engineering and Technology (ABET) accredited engineering programs [1]. While there are several models for the capstone experience, each tailored to the institutional and program goals of a specific program, most are project-based, and introduce or reinforce the engineering design process and activities [2] - [4]. In general, the capstone engineering design course emphasizes innovation through team project-based learning.

The capstone design course in the United States Air Force Academy's (USAFA) Department of Engineering Mechanics employs a multi-step design process which has been created specifically to facilitate maximum innovation: 1) Project definition and background research, 2) Customer needs analysis, 3) Functional description, 4) Ideation, 5) Concept selection, 6) Analysis and modeling, 7) Risk assessment and mitigation, 8) Prototyping and 9) Testing [5]. This process has been developed over many years through deliberate research into novel design methods, and the results have been published in numerous peer-reviewed publications [6]-[12]. The process emphasizes the ideation, or concept generation, stage in the design process. The process is ripe with possibility for infusion of creativity that can lead to the development of innovative products and systems. Along with the desired novelty, concepts must also be feasible in order to have promise as fielded products. This combination of desired novelty and required feasibility can be difficult to attain.

Typically, the design process pairs senior undergraduate mechanical and systems engineering students with a mentoring faculty member and, occasionally, a graduate student who is an expert in the area of "innovative design". The collaborative team works to solve a real-world problem through the application of various design techniques. In addition, the collaboration can improve or even identify enhanced design techniques and processes. For example, past research efforts improved the design method in two areas: 1) the understanding of how to develop and implement prototyping strategies which are effective and efficient [11] - [15] and 2) new methods to enhance ideation based on analogies to biological systems [16]. The sponsor organization research partners take keen interest in the design methodology research; oftentimes adopting these techniques into their own programs.

These past research efforts have focused on pioneering new engineering design *methods* that produce innovative solutions to engineering problems. The work performed here examines if the capstone design experience and the proposed creativity exercises *improve the human subjects' intrinsic ability to be creative*. This has not been rigorously examined within the USAFA Department of Engineering Mechanics' capstone design course, though anecdotal faculty observation and customer feedback suggests that such improvements occur. Enhancing students' creative ability is desirable for many reason, but in part because of the role creativity plays in numerous engineering student outcomes. In particular, ABET outcome 2, "an ability to apply engineering design to produce solutions that meet specified needs…" which is also a student outcome at the USAFA [1].

The goals of this multi-year experiment are to provide researched-based evidence on:

1) The efficacy of the capstone design experience at increasing individual student creativity.
2) The efficacy of creativity enhancing activities at increasing individual student creativity.
3) The efficacy of creativity enhancing activities at enhancing the innovation of undergraduate student design projects.

This work reports results after two years of experiments aimed at evaluating these questions. The capstone design experience used in the study has been developed over two decades and is heavily tailored toward maximizing innovation. The proposed creativity enhancing activities were created by Destination Imagination, a non-profit educational organization dedicated to teaching the creative process [28, 29].

2. Background and Motivation

Creativity is a construct that is commonly used, yet in research related terms, it evades consensus in definition [17] - [19]. This can undermine consistent findings when examining the efficacy of creativity enhancement and assessment. Although a single agreed upon definition has not been established, Plucker, et al.'s survey of research on creativity found that there appears to be some consensus that creativity has two basic characteristics: originality and usefulness [17]. For this study, the definition proposed by Plucker, Gehetto, and Dow will be used [18]:

> "Creativity is the interaction among aptitude, process, and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context." [18, pg. 90]

This definition encompasses the characteristics of originality and usefulness while acknowledging the characteristics that are useful to the engineering design process. Of importance is acknowledging the participation of the individual and the interaction of the group, as well as the social context in the design process. Since the capstone design course involves a group of students and advisors that interact to innovate in order to meet the needs of a customer-defined problem, this definition most appropriately acknowledges the breadth of the engineering design and education process. It also supports the notion that creativity can be assessed. The appropriate assessment of creativity requires that the assessment instrument must be consistent with the construct definition. As discussed below, the primary creativity assessment tool used here, the Torrance Tests of Creative Thinking (TTCT), may not comprehensively assess creativity according to this definition.

Plucker, et al.'s definition of creativity [18] is consistent with Guilford's view of the intellectual process of divergent thinking which is associated with the problem-solving processes related to tackling open-ended problems in which there is no unique, predetermined solution [19], [23]. Thompson and Lordan concluded that divergent thinking is significant in the process of working through open-ended projects if they involve fact finding, problem definition, and idea generation [23]. These steps are foundational to the capstone design course that is the basis of this study. The course guides students through the process of exploring and innovating as many ideas as possible using divergent thinking before applying convergent thinking to down-select from the wide range of ideas to those that most innovatively meet the customer needs, yet are feasible within the limitations of time, expertise, equipment availability, and financial support.

2.1 Creativity and research in engineering design and education

Over the years, research on creativity from the social sciences and the development and research into engineering design and innovation have converged with the examination of creativity in the engineering design process [20]. Creativity has been recognized as a critical, if not necessary, component in the success of the future of engineering design and innovation [21] - [26].

As the interest and research in creativity in the engineering design process has proceeded, work on ways to enhance and study creativity in the engineering design education community has also expanded [12], [21], [25], [26]. Since creativity has been deemed to be essential to engineering design success, can it be enhanced in its students? Sternberg [27] and others believe creativity can be developed and enhanced [18], [19]. Yasin and Yunus' meta-analysis review found that creativity enhancing activities such as creative problem solving and brainstorming techniques were able to produce medium to large effect sizes when applied in college or university settings [25]. Therefore, the engineering education community should be encouraged to foster the development of creativity in its students.

2.2 Creative problem solving activities

Yasin and Yunus reported that creative problem solving activities can be helpful in fostering creativity in undergraduate engineering programs [25]. In an effort to better understand the impact of this type of activity, it is helpful to use well-tested activities that were developed to promote creativity in the participants. A well-known source of creative problem-solving activities is from Destination Imagination (DI) and affiliates, which is a nonprofit educational organization that is dedicated to teaching the creative process to students around the globe [28]. The open-ended structure of DI allows learners to engage in deep inquiry and research particularly focused in the areas of STEAM (science, technology, engineering, the arts and mathematics). The educational experience provided by DI is founded on five primary tenets of unique pedagogy; no interference, resource awareness, clarifying questions, rapid ideation and implementation, and authentic self-expression.

Project-Based Learning (PBL) is another essential component of the DI educational experience and brings into play the following elements of PBL: It is learner focused, meaningful, contains real world content as well as deep inquiry and evaluation.

Utilizing the creative process and project based learning, as well as 21st century skills, DI teams of up to seven students annually collaborate on one of six year-long competitive team challenges. They also practice, and perform for competition, short Instant Challenges [33-39]. Instant Challenges (ICs) may be task-based (build a device to accomplish a task) [33, 35, 36, 38, 39], performance-based (create a story and perform it) [34, 37], or a combination and they typically last ten minutes or less. The teams have no prior knowledge of the challenge, so they must quickly understand the problem, ideate, and implement their solution. ICs are scored based on a defined rubric that is provided to the team, allocating points for accomplishing specific tasks inherent in the challenge, but also for overall creativity of their intended solution, and overall teamwork.

The creative process that is utilized by DI teams helps them to effectively approach problems and take solutions to an innovative level [29]. The divergent thinking process integrates Blooms Taxonomy [30], the scientific method, 21st century skills, collaborative problem solving, and the stages of practical inquiry. The creative process: Recognize, Imagine, Initiate & Collaborate, Assess, and Evaluate & Celebrate, is not linear but rather may loop back on it as new information presents itself and the team works to develop innovative solutions [29].

2.3 Motivation

The importance of creativity in the engineering design process has become increasingly apparent along with the need to foster it during the engineering education curriculum. This compels educators to seek ways to enhance creativity; preferably with techniques that are shown to be effective through credible research. Therefore, the ability to assess creativity within an engineering design curriculum is essential to understanding the efficacy of the program and its elements [25], [26]. More specifically, it is important to ascertain what activities lead to developing creativity during the educational process.

In an effort to infuse evidence-based creativity enhancing activities within the USAFA capstone design curriculum, the current two year research project was designed to implement and assess the efficacy of the activities as an integral part of the course. IC activities have been incorporated in the USAFA capstone design course previously, but their effects were not directly studied.

Nevertheless, faculty observations and customer feedback suggested that creativity and product innovation improvements occurred. Thus, sufficient anecdotal evidence existed to motivate further formal examination of the impact of IC activities on the USAFA engineering design process and capstone design course.

Since the underlying conceptual process of the capstone design course and the DI activity experience reflects the divergent thinking processes it is appropriate to use a commonly used assessment of divergent thinking, the Torrance Tests of Creative Thinking (TTCT) [25], [31].

3. Research Approach

The objective of this quasi-experimental study is to examine how engineering students' creativity develops throughout a capstone design course, as measured by TTCT Creative Index scores, and if additional exposure to IC activities in the capstone design course further enhances creativity. This data will allow faculty to determine; 1) the effectiveness of the capstone design course at enhancing individual creativity and 2) the effectiveness of creativity activities at enhancing individual creativity.

Over two academic years, the TTCT Figural Form A was administered to all students in the capstone design course on the second class meeting of the course to establish a baseline, before any content or other pedagogical interventions were employed. The students were divided into groups, as described below, to establish treatment and control groups. Every week, a designated portion of students participated in a creativity enhancing activity. The activities were proctored by a trained administrator to ensure consistent instruction and feedback across all activities. The TTCT Figural Form B was then re-administered at the end of the semester (approximately 14 weeks after Form A). The TTCT was administered by the same proctor for both administrations. The TTCT was scored by the Scholastic Testing Service to ensure accuracy and consistency.

3.1 Participants

The participants were undergraduate students enrolled in a senior-level undergraduate capstone course (*n = 93; females = 17; males = 76; mean age = 21.5 years*). Participants were divided into seven capstone project teams each year (14 teams total) by a multi-step process which included student-expressed interest in available projects, student major, and faculty input. The capstone project teams were assigned to either the control or treatment conditions prior to start of the semester. Two treatments are being considered here: 1) the innovative engineering design content of the capstone design course, and 2) creativity activities [33-39]. Twelve out of 14 teams received treatment one (engineering design content). The other two teams received a streamlined engineering design curriculum with a reduced emphasis on innovation, due to the nature of their project – a highly constrained collegiate automotive design/build competition – that is less-suited to the innovative engineering design treatment. On the other hand, the twelve treatment groups had very open-ended projects ripe for innovation. Ideally, more teams would be part of the control, but that would result in providing curricula to the students that are not optimal for their learning, or for the type of capstone project they are pursuing.

Six out of the 14 teams ($n = 37$) received treatment 2 (creativity activities), while the remaining four teams ($n = 56$) did not. These groupings are summarized in Table 1 below.

Table 1. Summary of distribution of participants in study groups.

	Treatment	Number of Teams	Number of Participants
1	Innovative Engr Design Content	12	70
	Control - Standard Engr Design Content	2	23
2	DI IC Creativity Activity Treatment	6	37
	Control - No Creativity Activities	8	56

3.2 The Torrance Tests of Creative Thinking

The Torrance Tests of Creative Thinking (TTCT) Figural Test is a test of divergent thinking using two batteries of assessments: Figural and Verbal [31]. The TTCT has been nationally normed for grade and age [41]. For this study, only the Figural test will be used because it more-closely resembles typical engineering design ideation. The age-based normed scores will be used. The grade-based norms include up to grade 13. Since the participants will be juniors (grade 15) and seniors (grade 16) in college, it was felt using grade 13 normative scores would not be appropriate. The Figural test is appropriate and has been nationally-normed for ages 5-20.

The Figural test takes approximately 45 minutes to complete which includes preliminary instructions and distribution/collection of materials. Participants are asked to draw and give a title to the pictures they create. From a normative scoring procedure (age), scores are computed for the five major areas of fluency, elaboration, originality, resistance to premature closure, and abstractness of titles, as well as an overall Creativity Index score. It should be noted that the TTCT assesses individuals, whereas, the definition of creativity given earlier [18] allows for group creativity and the capstone design curriculum and creativity activities are all performed within groups. It is possible that group creativity develops separately from individual creativity, as teams learn to work better together. Therefore, the data reported here may under-report enhancement of group creativity. That is to say, the results are likely conservative.

3.3 The Instant Challenge Activities

The creativity exercises used in this study were “Instant Challenges” (ICs) provided by Destination Imagination. The ICs were deliberately selected to be diverse, thus providing a variety of creativity practice. The ICs used are summarized in Table 2 below. It is expected that these exercises will help individuals and teams hone their creativity and imagination by utilizing quick thinking and rapid implementation of solutions.

Table 2. Summary of Instant Challenges used for creativity practice exercises [33]-[39].

IC Title	IC Type	Short Description
Balance of Power	Task	Build a cantilever structure to suspend weights over specified zones for points.
Bag Nabber	Performance	Perform a story backwards about a character who steals a bag filled with one or more mystery objects.

Two Out of Three	Combination	Given 3 unmarked boxes, select 2 and perform the challenge hidden within. These were; float marbles in water, build a bridge, or perform a skit.
Colorful Communication	Task	Communicate a set of orders to other members of the team using a grid board and colored cards.
Road Trip	Performance	Create and perform a story about a road trip.
Catch It If You Can	Task	Build a device(s) that launches ping-pong balls and a structure to catch them.
Ball Balancer	Task	Balance an assortment of balls (soccer, tennis, etc) on the top of a 4x4 post using provided materials.

3.4 Data Management

A Last Name Replacement Code (LNRC) consisting of alphabetic characters was used to protect the identity of the participants. Since the TTCT test booklets use only alphabetic characters as identifiers, random numbers could not be used. The first step in creating unique LNRCs is to generate a unique randomly generated 5-digit number for each participant. The actual LNRC is created by replacing each numeric-digit of the random number with a corresponding letter. Each participant's name was associated with a unique LNRC.

Example: Participant Name: Jane Doe   Last Name Replacement Code: GHLDB

4. Results

Data collected included TTCT testing, quantity of concepts developed by capstone team and faculty evaluation of quality and novelty of concepts proposed during the capstone design process.

4.1. TTCT Testing

The TTCT has been nationally-normed on data from ages five to twenty [41]. The normative scores will be used in the statistical analysis to determine if there are differences between the mean scores on the Figural test between the control and treatment group.

An evaluation of the basic assumptions of the *t*-test found that the samples were from independent samples, the scores were normalized based on age, and met Levene's test for homogeneity of variance [Form A sample: $F(19, 28) = 0.5914$, $p = 0.1185$; Form B sample: $F(19, 28) = 0.6004$, $p = 0.1253$].

Due to the restrictions of an academic environment, the participants were not randomly assigned. Therefore, it is important to establish that the groups were not unintentionally biased before treatment. An analysis of the Form A (pre-treatment) Creativity Index scores indicates that there is no statistical difference between the control and treatment groups on their initial assessment of creativity [$p = 0.591$].

The comparison of pre- and post-treatment TTCT Creativity Index scores, shown in Table 3, below, is expected to support the following hypotheses:

Hypothesis 1) Students who receive innovative engineering design content (treatment 1) during the capstone course will improve their mean Creativity Index scores on the second administration (Form B) of the TTCT Figural test.

Result: The group that received innovative engineering design content during the capstone course showed an overall improvement in mean Creativity Index of +0.54, while the control group actually showed a reduction in mean Creativity Index of -1.2. However, the calculated statistical significance of these changes in mean score are not strong. The p-value for the treatment group's improvement in mean score is 0.866, nearly indicating that the treatment produced a statistically significant improvement in CI. Similarly, the p-value for the control group was 0.826, nearly indicating that the treatment produced a statistically significant decrease in CI. That is to say, there is roughly equal statistical evidence that the treatment group improved Creativity Index while the control group decreased.

In addition to Creativity Index, the TTCT provides sub-scores in five categories: Fluency, Originality, Elaboration, Abstractness of Titles, and Resistance to Premature Closure. In the first year of the study, the treatment group showed a statistically significant increase in Originality [delta mean = 8.8, $p = 0.044$], while the control group did not, if anything, it decreased [delta mean = -7.3, $p = 0.464$]. Further, "Average Creativity" is the average of the five aforementioned categories. It differs from Creativity Index which is the average creativity plus bonus points for 13 "Strength Ratings" (Emotional Expressiveness, and Humor, for example). In this case, the treatment group demonstrated a somewhat significant change in Average Creativity [delta mean = 7.2, $p = 0.100$], while the control did not [delta mean = -1.6, $p = 0.776$]. These results provide additional evidence that the innovative engineering design content has a positive impact on individual student creativity.

Table 3. Summary results showing overall Creativity Index scores of the various student groups subject to this study (two-tailed, two-sample unequal variance *t*-tests)**.**

	Pre-Treatment Mean (Form A)	Post-Treatment Mean (Form B)	Delta Mean	*P-value*	Conclusion
Innovative Engr Design Content	115.4 *(n = 70)*	116.0	**0.54**	*0.866*	Hypothesis #1 supported
Control	119.5 *(n = 23)*	118.3	**-1.2**	*0.826*	
Creativity Treatment	117.7 *(n = 37)*	119.3	**1.6**	*0.713*	Hypothesis #2 supported
Control	115.6 *(n = 56)*	114.8	**-0.86**	*0.811*	

Hypothesis 2) Students who participate in the seven weekly DI IC creativity activities (treatment 2) will show a greater improvement in their mean Creativity Index scores than the control group on the second administration (Form B) of the TTCT Figural test.

Result: The group that received the seven weekly Destination Imagination creativity activities [33-39] showed an overall improvement in mean Creativity Index of +1.6, while the control group showed a decrease in mean Creativity Index of -0.86. The statistical significance of these changes in mean score are similar to hypothesis 1. The p-value for the treatment group's improvement in mean score is 0.713, nearly indicating that the treatment produced a statistically significant improvement in CI. Similarly, the p-value for the control group was 0.811, nearly indicating that the treatment produced a statistically significant decrease in CI. That is to say, there is roughly equal statistical evidence that the treatment group improved Creativity Index while the control group decreased.

As suggested above, and confirmed by the T-Test analyses, the study would certainly benefit from continued study and a larger sample size. The research is limited by capstone course enrollment, which totaled 93 for the two academic years encompassing the research to date. To improve the statistical quality of the conclusions, the experiment must be continued in subsequent years to increase the total sample size. The results reported here are promising and justify continuing the experiment in subsequent years.

4.2. Quantitative and Qualitative Analysis of Concepts

In the engineering design community, quantity, quality and novelty of concepts are widely accepted as reliable metrics for evaluating ideation and predicting innovation [43]. Therefore, in addition to TTCT testing, the capstone design teams in year one were evaluated for the quantity, quality and novelty of the concepts developed during their ideation phase of the design process. The goal of this analysis was to collect data to support the following hypothesis:

Hypothesis 3) Design teams composed of students who participate in the seven weekly DI IC creativity activities (treatment 2) will produce more innovation (greater quantity, quality and novelty of concepts [43]) throughout their capstone design projects as compared to the control.

Result: For quantity, the three design teams ($n = 20$) assigned to the treatment group produced an impressive 628 unique concepts across the three teams, or an average of 31.4 concepts per student. The three design teams in the control group ($n = 18$) produced 463 unique concepts, or 25.7 concepts per student. Clearly, the design teams that participated in the Destination Imagination creativity activities produced a higher quantity of concepts. Causality cannot be established because of other relevant variables, such as the personality, experience and expectation of the distinct faculty advisors mentoring each team.

To evaluate quality and novelty, department faculty were asked to make subjective evaluations of each team's top five concepts as presented during their Preliminary Design Review (PDR). There were difficulties with this survey approach. In particular, each team presented various numbers of final concepts and it wasn't clear to faculty which five concepts should be evaluated. As a result, faculty ratings were not necessarily performed on the same five concepts for a given team. In addition, not all faculty attended all PDRs, so the "jury" changed from one PDR to the next. To correct for this, final scores were compiled from only those faculty that attended all or most of the PDRs. In addition, this evaluation was not entirely blinded. Two of the six faculty evaluators were study authors and knew team distribution between control and treatment groups.

A rubric was provided to aid in assigning a score of 1 – 4 points for the quality and novelty of each concept.

The treatment group earned an average quality rating of 2.60 ($n = 46$) compared to the control average rating of 2.05 ($n = 54$). The treatment group earned an average novelty rating of 2.84 ($n = 46$) compared to the control average rating of 2.16 ($n = 54$). The treatment group—those design teams composed of students that participated in the DI IC creativity activities—were rated by experienced capstone design faculty as having produced more innovative concepts during their semester-long engineering design process. This is evidence to support hypothesis 3; once again, more data collected over several years would be helpful.

Finally, the study occurred over a nine week period, in which seven ICs were administered to the treatment 2 group. It was encouraging to observe that these design teams improved clearly and rapidly at completing the creativity challenges. The exercises were administered without prior coaching, but the faculty administrator would provide feedback at the conclusion of each activity. Over the seven challenges, the teams improved their inter-personal communication, teamwork, and ability to rapidly ideate and implement solutions. They also learned to quickly analyze the scoring rubric and determine the optimal strategy to implement a solution that would maximize their score, and not be distracted by other features that are not relevant to the score. Further, the students genuinely enjoyed the exercises, despite the time it took away from completing their design project, and they believe the exercises expanded their thinking to consider unexpected solutions. The most satisfying result of this study was observing (typically introverted) engineering students completely immerse themselves in a performance skit, complete with sound effects and wild gesticulations, without shame – fully focused on beating their competition.

5. Limitations

This paper provides the initial results of a multi year study. At this time, the most prominent limitation is the small sample size. The current sample size yields measurable differences in the mean Creativity Scores as a result of participation in the activities, but the statistical significance is not strong.

Since many of the project groups have different faculty advisors, there is a possibility that the influence of the advisors on the engineering design experience and possibly the change in creativity as a function of participation in the course may be different because of the diverse backgrounds of the advisors. Since advising faculty and staff change from year to year, it may dampen detectable differences across the life of the study.

The selection and use of the seven activities was constrained by the time available within the fall semester. The USAFA Mechanical Engineering curriculum is designed for a full academic year, and the student teams continue to learn and develop from repeated practice within a year and from year-to-year. It could be that more prolonged exposure to the activities may provide a stronger effect due to increased soak time.

The study was not entirely blinded. It was apparent to the students that received treatment 2 that they were performing exercises intended to increase their creativity. One might suspect that this knowledge could bias them in a way that affects their performance on the assessments. It is difficult to quantify level of effort, but, if anything, the opposite effect occurred. The students enjoyed doing the creativity exercises, but complained that they usurped project time. The treatment teams were asked to spend 20-30 minutes of valuable class time each week to perform the exercises, while the control groups were free to work on their projects. If anything, the control group had additional time to perform concept ideation than the treatment group.

For treatment 1 (innovative engineering design content), as stated above in Section 3, the content delivered to each team was chosen such that each team would have the optimal curriculum for their given project. This division of content would have occurred with or without the study, so the students should not have felt that they were, in any way, short-changed.

Individual student effort applied to the pre- and post-treatment TTCT is also a concern. In any standardized testing we must rely on the students' integrity to provide their best effort, whether they are part of a treatment or not. In a review of the reliability of the TTCT, Kim points out:

> "According to the TTCT manuals of 1966 and 1974, the test–retest reliability coefficients have ranged from .50 to .93, which is not so high. Torrance (1974) indicated that motivational conditions affect the measurement of creative functioning, which could explain the low test–retest reliability." [42, pg. 6]

Though these findings are dated, it is possible that administering two TTCTs in a 14 week period could have a significant dampening effect on the re-test scores. Additionally, it is likely that motivation had a negative impact on this study. Certain students *reduced* their Creativity Index scores over the study period by 52, 35, 28 and 26 points. Did these students not provide their best effort during the re-test? Other evidence suggests this is likely: in year two of the study, anonymous student course feedback specifically expressed dissatisfaction about being asked to take the final TTCT exam (Form B) on the last day of classes. In subsequent years, the administration of the test will occur at a less-stressful time and may include compensation (such as complimentary lunch) to improve student attitudes. Perhaps administering the test at the end of the year (with 36 weeks or more of separation), rather than the end of the semester would be more reliable, and would provide more statistically significant changes in Creativity Index.

6. Conclusions

Students in an undergraduate senior capstone design course were administered the TTCT to establish their incoming Creativity Index. They were assigned to 5-8 person design teams which were grouped into treatment and control groups to receive some combination of two treatments intended to enhance their individual creativity and innovation of their capstone design project. The treatments were innovative engineering design process content and seven weekly Destination Imagination "Instant Challenge" creativity activities [33-39]. At the conclusion of these treatments, the students were re-tested for Creativity Index (CI).

The comparison between pre- and post-treatments TTCTs indicated that both treatments had a positive effect on individual creativity. The Treatment 1 group showed a mean increase in CI of 0.54 while the control showed a decrease of -1.2 and this result was highlighted in year one by a statistically significant increase in Originality [delta mean = 8.8, $p = 0.044$] and Average

Creativity [delta mean = 7.2, p = 0.100]. In summary, Treatment 1, the innovative engineering design process curriculum, improved individual creativity as measured by a widely-accepted standardized creativity test.

The Treatment 2 group showed a mean increase in CI of 1.6, compared to the control which had an decrease of -0.86. Further, the relative innovation of the design teams' concepts were evaluated by quantity, quality and novelty. The teams that participated in the seven weekly creativity activities demonstrated a clear advantage in all three categories. In summary, Treatment 2, the weekly creativity exercises, improved individual creativity as measured by a widely-accepted standardized creativity test and improved the relative innovation of the design teams' concepts.

This work reports on the findings of a two-year study and the results obtained thus far are very encouraging; trending in the right direction. The primary flaw is the low sample size which limits the statistical significance of the changes in student performance over the study period. Therefore, the study should be continued to obtain more data over larger sample sizes, thus improving the reliability of the data and validity of the creativity enhancing methods. Nevertheless, there is sufficient evidence presented here to justify using Destination Imagination IC creativity enhancing activities as learning experiences to enhance individual creativity and design project innovation in undergraduate capstone design students.

Acknowledgements

The authors are grateful to Destination Imagination for developing and sharing the Instant Challenge creativity activities and to the cadets in the Department of Engineering Mechanics for their participation in the study.

References

1. Engineering Accreditation Commission, "Criteria for accrediting engineering programs, 2014 – 2015," [online]. Available: http://www.abet.org/, Accessed on: Jan. 30, 2015.
2. Marin, J. A., J. E. Armstrong, and J. L. Kays, "Elements of an optimal capstone design experience." *Journal of Engineering Education*, vol. 88, no. 1, pp. 19-22, 1999.
3. J. Zable, "Guest Editorial: 2007 National Capstone Design Conference," *Advances in Eng. Edu.*, vol. 2, no. 1, pp. 1-4, 2010.
4. L. J. McKenzie, M. S. Trevisan, D. C. Davis, and S. W. Beyerlein, "Capstone design courses and assessment: A national study," in *Proc. 2004 Amer. Soc. Eng. Edu. Annu. Conf. and Expo.* Salt Lake City, UT.
5. K. Otto and K. Wood. *Product Design: Techniques in Reverse Engineering and New Product Development*. Upper Saddle River, NJ, USA: Prentice Hall, 2012.
6. IBM, "Capitalizing on Complexity: Insights from the Global CEO Study", 2010.
7. M. Anderson, C. Perry, B. Hua, D. Olsen, D. Jensen, J. Parcus, and K. Pederson, "The Sticky-Pad Plane and other innovative concepts for perching UAVs", *AIAA Annu. Conf.* Orlando, FL, Jan 2009.
8. C. Cooper, C. Bruce, M. Anderson, S. Galyon-Dorman, and D. Jensen, "Designettes in Capstone: Initial design experiences to enhance students' implementation of design methodology", *Proc. Amer. Soc. Eng. Edu. Annu. Conf.*, Seattle, WA, June 2015.
9. K. Fu, J. Murphy, K. Wood, M. Yang, K. Otto, D. Jensen, and K. Wood, "Design-by-Analogy: Experimental evaluation of a functional analogy search methodology for concept generation improvement," *Res. Eng. Des.*, vol. 26, pp. 77-95, 2005.

10. J. Murphy, K. Fu, K. Otto, M. Yang, D. Jensen, and K. Wood, “Function Based Design-By-Analogy: A functional vector approach to analogical search,” *ASME J. Mech. Des.*, vol. 136, pp. 101102-1- 101102-16, Oct. 2014.
11. B. Camburn, B. Dunlap, T. Gurjar, C. Hamon, M. Green, D. Jensen, R. Crawford, K. Otto, and K. Wood, K., “A systematic method for design prototyping,” *ASME J. Mech. Des.*, vol.137, no. 8, pp. 081102-7-081102-12, Aug. 2015.
12. C. White, D. Jensen, and K. Wood, “From brainstorming to C-Sketch to principles of historical innovators: Ideation techniques to enhance student creativity,” *J. STEM Edu.*, vol. 13, no. 5, pp. 12-25, Oct. - Dec. 2012.
13. B. Camburn, B. Dunlap, V. Viswanathan, J. Linsey, D. Jensen, R. Crawford, K. Otto and K. Wood, “Using design problem characteristics to build a prototyping strategy.” *In Proc. 120th ASEE Annu. Conf.* Paper ID #6479, Atlanta, GA, USA, Jun. 23-26, *2013*
14. B. A. Camburn, B. U. Dunlap, R. Kuhr, V. K. Viswanathan, J. S. Linsey, D. D. Jensen, R. H. Crawford, K. Otto and K. L. Wood “Methods for prototyping strategies in conceptual phases of design: Framework and experimental assessment.” *In Proc. ASME 2013 Int. Des. Eng. Tech. Conf. and Comput. and Inform. Eng. Conf.*, Portland, OR, USA, Aug. 2013, pp. V005T06A033-V005T06A033.
15. B. A. Camburn, K. H. Sng, K. B. Perez, K. Otto, K. Wood, D. Jensen, and R. Crawford. “The way makers prototype: Principles of DIY design.” *Proc. ASME 2015 Int. Des. Eng. Tech. Conf. and Comput. and Inform. Eng. Conf., Boston, MA, USA, Aug 2-5, 2015*, pp. V007T06A004-V007T06A004).
16. M. Anderson, J. Onyechi, T. Yamazaki, K. Wood, and D. Jensen, “Mind map for biologically inspired covert visual systems: A pilot study,” *Proc. ASEE Rocky Mountain Section Conf.*, Provo, UT, 2017.
17. R. E. Mayer, “Fifty years of creativity research,” in *Handbook of Creativity*, R. J. Sternberg, ed. Cambridge, UK: Cambridge University Press, 1999, pp. 449-460.
18. J. A. Plucker, R. A. Beghetto, and G. T. Dow, “Why isn’t creativity more important to educational psychologists? Potentials, pitfalls, and future directions in creativity research,” *Educational Psychologist,* vol. 39, no. 2, pp. 83-96, 2004.
19. J. P. Guilford, “The structure of intellect,” *Psychological Bulletin*, vol. 53, no. 4, pp. 267-293, Jul. 1956.
20. T. J. Howard, S. J. Culley, and E. Dekoninck, “Describing the creative design process by the integration of engineering design and cognitive psychology literature,” *Des. Studies,* vol. 29, no. 2, pp. 160-180, Mar. 2008.
21. S. R. Daly, E. A. Mosyjowski, and C. M. Seifert, “Teaching creativity in engineering courses,” *J. Eng Edu*., vol. 103, no. 3, pp. 417-449, Jul. 2014.
22. T. Howard, S. Culley, and E. Dekoninck, “Creativity in the engineering design process,” *Int. Conf. Eng. Des*., ICED’07, Paper ID #: 887, Paris, FR, Aug. 28-31, 2007.
23. G. Thompson and M. Lordan, “A review of creativity principles applied to engineering design,” *Proc. Institution Mech. Engineers*, vol. 213, no. 1, pp. 17-31, 1999.
24. D. H. Cropley, “Promoting creativity and innovation in engineering education,” *Psychology Aesthetics, Creativity, Arts*, vol. 9, no. 2, pp. 161-171, 2015.
25. R. M. Yasin and N. S. Yunus, “A meta-analysis study on the effectiveness of creativity approaches in technology and engineering education, *Asian Social Sci*., vol. 10, no. 3, pp. 242-252, 2014.
26. C. Charyton and J. A. Merrill, “Assessing general creativity and creative engineering design in first year engineering students, *J. Eng. Edu*., pp. 145-156, 2009.
27. R. J. Sternberg, “The nature of creativity,” *Creativity Res. J*., vol. 18 no. 1, pp. 87-98, 2006.
28. Destination Imagination Inc., [online]. Available: https://www.destinationimagination.org/, Accessed on: Dec. 29, 2017.
29. Destination Imagination Inc., “Educational foundations of Destination Imagination,: in “Destination Imagination Roadmap 2017-2018,” Cherry Hill, NJ, pp. 2-10, 2017.
30. Bloom, B. S., (1984), Taxonomy of Educational Objectives Book 1: Cognitive Domain, Addison Wesley Publishing Company, White Plains, NY.
31. E. P. Torrance, *Torrance Tests of Creative Thinking*. Bensenville, IL: Scholastic Testing Service, 1990.
32. J. A. Plucker and J. S. Renzulli, “Psychometric approaches to the study of human creativity,” in Handbook of Creativity, R. J. Sternberg, ed. Cambridge, UK: Cambridge University Press, 1999, pp. 35-61.
33. Students for a Creative Iowa, “Balance of Power,” Instant Challenges, [online]. Available: http://www.cre8iowa.org. Accessed on: Jul. 15, 2017
34. Students for a Creative Iowa, “Bag Nabber,” Instant Challenges, [online]. Available: http://www.cre8iowa.org. Accessed on: Jul. 15, 2017
35. Destination Imagination Inc. “Two Out of Three,” Instant Challenges, Cherry Hill, NJ, 2009.

36. Students for a Creative Iowa, “Colorful Communication,” Instant Challenges, [online]. Available: http://www.cre8iowa.org. Accessed on: Jul. 15, 2017
37. Destination Imagination Inc. “Road Trip,” Instant Challenges, Cherry Hill, NJ, 2009.
38. Destination Imagination Inc. “Catch It If You Can,” Instant Challenges, Cherry Hill, NJ, 2014.
39. Destination Imagination Inc. “Ball-Balancer,” Instant Challenges, Cherry Hill, NJ, 2014.
40. E. P. Torrance, Torrance Tests of Creative Thinking: Norms-technical manual, figural forms A and B. Bensenville, IL: Scholastic Testing Service, 2008.
41. E. P. Torrance, *Torrance Tests of Creative Thinking: Norms-Technical Manual Figural (streamlined) Forms A & B*. Bensenville, IL: Scholastic Testing Service, 1990.
42. K.H.Kim, “Can We Trust Creativity Tests? A Review of the Torrance Tests of Creative Thinking (TTCT),” *Creativity Research Journal*, Vol. 18, No. 1, 3-14, 2006.
43. Shah, Jami J., and Noe Vargas-Hernandez. "Metrics for measuring ideation effectiveness." *Design studies*, Elsevier Science, Great Britian, Vol. 24.2, pg. 111-134, 2003.