Comparisons of Design Thinking for Engineering Education

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ABSTRACT

Design thinking ability is vital for engineers who are tasked with solving society's toughest sustainable development challenges. Prior research identified that the percentage of design thinkers among freshmen engineering students is greater than the percentage among the general population. However, engineering education's lack of attention to fostering creative ability may cause the design thinking ability of senior engineering students to suffer. The research addressed in this thesis compares the design thinking ability of engineering students across age groups, and compares design thinking ability between the design disciplines of engineering and architecture. To draw design thinking comparisons between these groups, a survey with a nine item design thinking instrument was distributed nationally to freshmen engineering students (n= 2,158), senior engineering students (n= 1,893), and senior architecture students (n= 336). The survey instrument was validated by conducting confirmatory factor analysis on the senior engineering and senior architecture samples' data. The Analysis of Variance (ANOVA) test was utilized to statistically compare scores across sample groups. Both the freshmen engineering students (2.80) and senior architecture students (3.30) scored significantly higher on the design thinking scale than senior engineering students (2.59). These results have important implications for engineering educators as engineering education may contribute to a decrease in design thinking among senior engineering students. A lower design thinking score among seniors was consistent across all engineering sub-disciplines and should be of concern to engineering educators, since design thinking skills are critical for the development of engineering solutions to grand societal challenges.

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GENERAL AUDIENCE ABSTRACT

Design thinking is a way of thinking about the design process which places the user at the center of the design. Thinking about design in this way is a vital ability for engineers and other design professionals to develop because it enables them to solve “wicked” problems like sustainable development challenges. Wicked problems are those which are difficult to solve due to the number of conflicting components involved. Prior research has found that design thinkers are more prevalent among engineering students in their first year of study than among students in other majors. However, engineering education does not attribute much attention to the development of creative ability which could cause the design thinking ability of engineering students in their final year of study to be worse than the ability of those in their first year, as well as worse than the ability of students who study other design disciplines like architecture. This study compared the design thinking abilities of engineering students in their final year of study to engineering students in their first year and to architecture students in their final year. The goal of making these comparisons was to explore if engineering education helps or hinders the development of design thinking. A survey with nine questions related to design thinking was distributed nationwide. The data from the survey was collected and statistically analyzed. The results showed that the design thinking ability of engineering students in their final year was significantly lower than the ability of first year engineering students and significantly lower than the ability of final year architecture students. A decrease in design thinking ability between freshmen and senior year must be addressed by engineering educators. The National Academy of Engineers and industry leaders are calling for the development of engineers who are design thinkers, and the results of this paper suggest that some changes may need to occur within the engineering education curriculum to accommodate this need.

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Finally, I would like to thank my parents who always encouraged me to go further with my education and for their infinite support and love.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ATTRIBUTION

This foreword describes the contribution of each of the authors for the two manuscripts within this thesis document.

Manuscript 1:

Emma Coleman-Emma reviewed the relevant literature, developed the methods, analyzed the data, and wrote the manuscript which incorporates comments and feedback from the other authors.

Tripp Shealy- Tripp developed the concept for the research and helped finalize research questions and methods. He also offered multiple rounds of feedback and comments on the manuscript.

Jacob Grohs- Jake helped guide the methods and provided resources and feedback on results of the data analysis. He also provided feedback on the manuscript.

Allison Godwin- Allison provided the software and hardware utilized to digitalize the data and provided feedback on the manuscript.

Manuscript 2:

Emma Coleman- Emma developed the research concept, reviewed the relevant literature, developed the methods, analyzed the data, and wrote the manuscript which incorporates feedback and comments from the other authors.

Tripp Shealy- Tripp helped finalize the research questions and provided multiple rounds of feedback and comments on the manuscript.

Frederick Paige-Freddy provided multiple rounds of feedback and comments on the manuscrip

INTRODUCTION

Numerous studies (Beckman and Barry 2007, Schaar, Rains and Jacobson 2015, Levine, Agogino and Lesniewski 2016, Ercan, Sale and Kristian 2016, Zancul, et al. 2017, Strimel and Kelley 2017) have evaluated the benefits of incorporating design thinking approaches into engineering pedagogy. Benefits include increased engineering agency as well as increased functionality and innovation in design products (Zancul, et al. 2017). However, despite the breadth of prior research documenting the positive effects of teaching design thinking in engineering, the majority of these works are limited to individual classroom experiments and case studies. Many questions remain to be answered like, are engineering students nationally developing design thinking ability? Do students become better design thinkers through their undergraduate studies? What differences exist between engineering disciplines? And how do design thinking abilities of engineering students compare to abilities of students in other design fields? These are some of the practical questions the manuscripts within this thesis will answer.

This document contains two manuscripts that focus on comparisons of design thinking ability. Chapter 1 is a cross-sectional quantitative study that compares design thinking between freshmen and senior engineering students by statistically analyzing over 4,000 student responses to a design thinking survey instrument. Chapter 1 identifies areas within engineering education that could be improved to foster design thinking ability and provides recommendations for engineering educators. Chapter 2 is a quantitative study that compares design thinking between engineering and architecture students who are within their final year of undergraduate studies by statistically analyzing student responses to the design thinking survey instrument, also utilized for analysis in Chapter 1. Architecture students were chosen for comparison in Chapter 2 because their curriculum places a targeted emphasis on design thinking. Chapter 2 identifies pedagogical approaches within architecture that could be applied to engineering education to improve its design thinking curriculum.

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Abstract

Background Prior researchers developed an instrument to quantitatively measure perceived design thinking ability of engineering students based on five design thinking traits, and they validated the instrument through exploratory factor analysis. They found that the freshmen engineering collegiate population consists of a higher percentage of design thinkers (41%) when compared to the population of freshmen collegiate students as a whole (31%). However, a highly technical engineering course load which hinders creative thinking may decrease the perceived design thinking ability of senior engineering students.

Purpose In contrast to numerous prior qualitative studies on design thinking within engineering education, this study takes a quantitative approach to evaluate design thinking of engineering students. This article makes a cross-sectional quantitative comparison of the perceived design thinking ability between national samples of first-year and senior engineering students. It also examines differences in design thinking between engineering disciplines.

Design/Method We surveyed a national sample of senior engineering students and compared their results from the design thinking instrument to the results from a national sample of freshmen engineering data collected in 2012. One-way ANOVA tests were used to compare average design thinking scores across sample groups and Cohen's *d* was calculated to analyze effect size. Comparisons of design thinking score were also broken down by design thinking trait and engineering discipline. To contribute to betterment of the instrument, we conducted a confirmatory factor analysis utilizing the senior engineering student data.

Results First-year engineering students scored significantly higher (2.80) on the design thinking scale than senior engineering students (2.59) by an effect size of 0.4. This relatively small difference in design thinking score can be explained by the fact that the senior engineering sample performed significantly worse on the feedback seeking and experimentalism design thinking traits, but significantly better on the integrative thinking and collaboration design thinking traits. No significant differences in design thinking scores were found between engineering disciplines among senior students.

Conclusions Engineering education may contribute to a decrease in design thinking among senior engineering students. Feedback seeking and experimentalism are traits that engineering educators should specifically develop in their students to improve perceived design thinking ability. Incorporation of user-centered design and divergent thinking in the engineering classroom are recommended as avenues to better foster feedback seeking and experimentalism. We also offer recommendations to improve the design thinking instrument for future researchers.

Keywords design thinking, survey, quantitative, national sample, cross-sectional study

Introduction

Engineering education has been predominately guided by an "engineering science" model since the 1950s (Dym, Agogino, Eris, Frey, & Leifer, 2005). Between 1935 and 1965, engineering curricula were modified from hands-on, practice-based approaches to emphasize mathematical modeling and theory-based approaches, mandating coursework in the engineering sciences. In decades following the shift, there was a growing concern that emphasis on engineering science was too heavy (Froyd, Wankat, & Smith, 2012). This emphasis on engineering science resulted in concern that the problems of focus within formal engineering education were out of alignment with real-world societal problems (Douglas, Koro-Ljungberg, Therriault, Lee, & McNeill, 2012; Atman, Chimka, Bursic, & Nachtmann, 1999). In the past decade, industry leaders, academics, and ABET standards have expressed a renewed interest in design and recognized the importance of design education for teaching engineers how to solve real world, open-ended problems (Dym, Agogino, Eris, Frey, & Leifer, 2005). Focusing on design within engineering has been identified as important because it requires students to synthesize knowledge from their theoretical, engineering science courses to solve larger societal problems.

Artifacts of the progression of engineering design education include capstone design courses offered during the senior year of engineering curricula and cornerstone courses offered during the first-year (Froyd, Wankat, & Smith, 2012). However, there is wide variation in engineering design pedagogy among these courses (Bazylak & Wild, 2007). One pedagogical approach to engineering design is design thinking which has been claimed as a beneficial approach for solving some of society's most complex engineering challenges (Blizzard 2013, Brown 2008). Developing engineers who are design thinkers is a need recognized by the National Academy of Engineers and industry leaders because of design thinkers' ability to handle complex, open-ended, and ill-defined societal problems (Dym, Agogino, Eris, Frey, & Leifer, 2005; Brown, 2008). According to Brown (2008), an industry leader of the global design company IDEO, design thinking is defined as "a human-centered, creative, iterative, and practical approach to finding the best ideas and ultimate solutions to the world's greatest problems" (p. 92). Through his work with IDEO, Brown defined the now popularized design thinking process- empathize, define, ideate, prototype, test- and he also defined key character traits that design thinkers must possess (Brown, 2008).

According to Brown, there are five key traits that contribute to a design thinking mindset: empathy, optimism, integrative thinking, collaboration, and experimentalism (Brown, 2008). The research presented in this paper analyzed design thinking with a validated survey instrument (Blizzard, et al., 2015) that was developed based on Brown's five design thinking traits. Blizzard et al. (2015) used this instrument to evaluate design thinking of first year students. To build on Blizzard et al.'s (2013, 2015) prior research, the purpose of our study was to collect and analyze design thinking data from a national sample of senior engineering students. We distributed Blizzard et al.'s (2015) five factor design thinking instrument in 2018 to senior engineering students and then compared our senior results with the first-year results that were collected through Blizzard et al.'s survey in 2012.

There is a breadth of research documenting the positive effects of teaching design thinking in engineering, but the majority of prior experimental design is limited to individual classroom experiments and case studies. Numerous studies evaluate the benefits of incorporating design thinking approaches into engineering pedagogy on a case study basis (Beckman & Barry, 2007; Schaar, Rains, & Jacobson, 2015; Levine, Agogino, & Lesniewski, 2016; Ercan, Sale, & Kristian, 2016; Zancul, et al., 2017; Strimel & Kelley, 2017). The benefits include increased engineering agency as well as increased functionality and innovation in design outcomes (Zancul, et al., 2017). A limitation of these prior case studies is a broad understanding of how engineering students are nationally developing design thinking skills. Many additional questions remain to be answered like: Do engineering students become better design thinkers through their undergraduate studies? And do differences exist between engineering disciplines? Research results presented in this article answer these questions using a cross-sectional quantitative approach that statistically compares responses from national samples of first-year (n = 2,505) and senior (n = 2,095) engineering collegiate students. A recent Institute for Education Sciences report indicates that answering these kinds of large-scale descriptive questions can be particularly useful for identifying the "types of interventions needed to understand the landscape of needs and opportunities," (Loeb, et al., 2017, p. 1). In other words, through investigation of these descriptive questions, our study can provide insight into the types of interventions that can be utilized within engineering education to meet the needs of design thinking.

Background

Applying a Design Thinking Theoretical Framework to Engineering Design

Design is explored broadly in four topic areas: 1) symbolic and visual communications, 2) material objects, 3) activities and organized services, and 4) complex living, working, playing, and learning systems or environments (Buchanan, 1992). The broad area of "complex living, working, playing, and learning systems or environments," traditionally includes the design discipline of engineering (Buchanan, 1992, p. 10). Defined more technically by engineering researchers, design is a "systematic intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints" (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 104). Engineering researchers have also identified specific skills necessary for engineering designers including the ability to: 1) tolerate ambiguity through a divergent-convergent thinking process, 2) think in terms of the big picture, 3) handle uncertainty, 4) make decisions, 5) think as part of a team in a social process, and 6) think and communicate in the several languages of design (Dym, Agogino, Eris, Frey, & Leifer, 2005).

Design thinking is a theoretical approach to design that can be applied to engineering curriculum. For instance, design thinking pedagogy has been incorporated into capstone design courses of a wide-range of disciplines including biomedical, industrial, electrical, and mechanical engineering (Schaar, Rains, & Jacobson, 2015; Levine, Agogino, & Lesniewski, 2016; Ercan, Sale, & Kristian, 2016; Zancul, et al., 2017; Strimel & Kelley, 2017). Mechanical engineering has a historical reputation for its focus on design (Godfrey, 2014), and engineering students in the mechanical, materials, and electrical disciplines have a significantly higher expectation ($p < 0.001$) to invent and design things over the course of their engineering education (Potvin, et al., 2013). However, design thinking is not a widespread design approach within these disciplines even though they may place more emphasis on engineering design. Engineering students in the biomedical ($p < 0.01$) and environmental ($p < 0.001$) disciplines have a significantly higher expectation to help others through their career (Potvin, et al., 2013) which is more consistent with the empathetic design approach that design thinking requires (Koppen & Meinel, 2015).

Prior research has shown that there are benefits associated with the design thinking approach, although it is still largely considered an experimental approach to engineering design education. One study showed that teaching with a design thinking approach in an engineering capstone course produced more innovative and functional design outcomes and contributed to increased engineering agency among students (Zancul, et al., 2017). Despite the ability of the design thinking approach to increase engineering agency and to guide students towards innovative solutions, the university where the study was conducted maintained a traditional engineering design course as the required course and offered the design thinking course as an optional elective (Zancul, et al., 2017). Decisions such as these are a missed opportunity for engineering educators to encourage the design thinking approach in senior design courses. Aside from the design thinking approach being a marginal consideration, engineering education is generally bookended with a cornerstone design course in the first-year year, a capstone design course in the senior year, and a highly technical course load in between (Froyd, Wankat, & Smith, 2012). This format of engineering design education along with a lack of priority given to the design thinking approach may have negative implications for design thinking of senior students.

A lack of priority given to design thinking within engineering education manifests itself in the lack of value attributed to creative skill development (Cropley, 2015). Prior research has shown that creativity decreases over the course of an engineering degree (Sola, Hoekstra, Fiore, &

McCauley, 2017) which is problematic when discussing design thinking because creativity impacts the design thinking approach. For example, divergent thinking, or the generation of ideas, is an aspect of creative thinking (Treffinger, Young, Shelby, & Shepardson, 2002) that directly impacts the experimentalism trait of design thinkers (Brown, 2008). In addition to a decrease in creativity (Sola, Hoekstra, Fiore, & McCauley, 2017), divergent thinking has been found to remain stagnant over the course of an engineering degree (Bennetts, Caldwell, Cheeley, & Green, 2017). While the progression of creativity and divergent thinking has been evaluated over the course of an engineering degree, the progression of design thinking has not. Our research fills this gap by quantitatively evaluating the progression of design thinking from first-year to senior students utilizing a cross-sectional study. The following section discusses the origins of the instrument that was utilized to measure design thinking.

Origins of the Design Thinking Instrument

Design thinking is an approach that can be applied to engineering design pedagogy and is a separate entity from engineering design. However, design thinking traits are similar to engineering design skills. The engineering design skills defined by Dym et al. (2005) can be summarized through design thinking traits defined by Tim Brown (2008), the founder of the design firm IDEO. For example, Brown's design thinking trait of collaboration defined as the ability to work with many disciplines and willingness to experience other fields (Brown, 2008) is analogous to Dym et al.'s skill "thinking and communicating in several languages of design." (Dym, Agogino, Eris, Frey, & Leifer, 2005, p. 104). Table 1 compares Brown's design thinking traits with Dym et al.'s engineering design skills.

Table 1. *Parallels between engineering designers and design thinkers*

Skills of Engineering Designers	Traits of Design Thinkers
Ability to tolerate ambiguity and handle uncertainty	Experimentalism- willingness to ask questions and take new approaches to problems
Big picture thinking	Integrative Thinking- ability to analyze holistically to develop novel solutions

Thinking as part of a team in a social process	Empathy- Ability to adopt the psychological viewpoint of others in everyday life
Thinking and communicating in the several languages of design	Collaboration- Ability to work with many disciplines and willingness to experience other fields
Ability to handle uncertainty and think in terms of the big picture	Optimism- Refusal to back down from challenging problems

Note. Skills of engineering designers were taken from Dym et al. (2005) and traits of design thinkers were taken from Brown (2008).

Given the similarities between skills of Dym et al.'s engineering designers and Brown's design thinker traits, Brown's traits were used as the theoretical framework for creation of the design thinking instrument (Blizzard, et al., 2015). Brown's framework was chosen in favor of Dym et al.'s framework because Brown is a leading authority on design thinking within the design industry (Brown, 2008). An industry driven evaluation of design thinking was a priority for this study because we wanted to evaluate engineering students' ability to be design thinkers outside of a classroom setting. This priority relates back to the concern that the current technical focus of engineering curriculum is preventing the development of engineers who can solve open-ended and ill-defined problems within the real-world (Douglas, Koro-Ljungberg, Therriault, Lee, & McNeill, 2012).

The design thinking instrument based on Brown's framework of the five design thinker traits includes nine items and was developed by Blizzard et al. (2015) (Table 2). In 2012, Blizzard et al. administered this design thinking instrument in a survey titled Sustainability and Gender in Engineering (SaGE) to a national sample of 7,451 first-year collegiate students from 59 U.S. institutions (Shealy, et al., 2016). After data collection, Blizzard et al. (2015) conducted an exploratory factor analysis (EFA) on the design thinking instrument that revealed a five factor structure where each factor corresponded to one of Brown's design thinking traits. In recognition that empathy, as defined by Brown, is a challenging construct to measure, the instrument developed by Blizzard et al. (2015) sought to measure the feedback seeking aspect of empathy. In order to utilize Blizzard et al.'s (2015) data for a cross-sectional comparison with senior engineering students, we did not revise the instrument for this study. However, we did conduct a confirmatory factor analysis, discussed in the Methods section, and we provide recommendations for future revisions to the instrument in the Conclusions section.

Table 2. *Design thinking instrument*

Design Thinking Characteristics	Survey Questions
Feedback Seeking- willingness to seek input from others to make decisions and change directions.	I seek input from those with a different perspective from me.
	I seek feedback and suggestions for personal improvement.
Integrative Thinking- ability to analyze holistically to develop novel solutions.	I analyze projects broadly to find a solution that will have the greatest impact.
	I identify relationships between topics from different courses.
Optimism- refusal to back down from challenging problems.	I can personally contribute to a sustainable future.
	Nothing I can do will make things better in other places on the planet.
Experimentalism- willingness to ask questions and take new approaches to problem solving.	When problem solving, I focus on the relationships between issues.
Collaboration- ability to work with many disciplines and willingness to experience other fields.	I hope to gain general knowledge across multiple fields.
	I often learn from my classmates.

Note. Design thinking characteristics were taken from Brown (2008) and survey questions were taken from Blizzard (2015).

Results from the design thinking instrument in Blizzard's survey found that engineering first-year students had a statistically significant higher percentage (41%) of design thinkers when compared to the entire first-year student population (31%). Women (52%) made up a higher percentage of design thinkers than men (38%, 10% did not report gender), and design thinkers were higher academic achievers across a combined academic index. Specific interest in environmental engineering was a positive predictor of a high design thinking score (Blizzard, 2013). While this important work by Blizzard (2013) validated the instrument and began to describe perceived design thinking ability of engineering students, the freshman snapshot does not provide insight into how undergraduate engineering curricula might impact design thinking over time. Blizzard (2013) recognized this limitation and identified exploring design thinking at the conclusion of an engineering degree as an area of future study. Given the demand from industry for engineering programs to develop design thinkers, it is vital that we understand the collective impact that formal engineering education has on the development of perceived design thinking ability.

Methods

Research Design

The overall objective of the research presented in this paper was to better understand the effects of engineering education on design thinking. The specific questions asked were, (RQ1) How do the self-reported design thinking abilities of senior and first-year engineering students vary? (RQ2) How do the self-reported design thinking abilities of engineering disciplines vary among the senior engineering student sample?

Based on prior literature, the hypothesis is (H1) design thinking scores will decrease between first-year and senior year due to a heavily detailed engineering course load, consistent with an engineering science pedagogical model that does not value the design thinking approach. The second hypothesis (H2) is senior environmental engineering students will have significantly higher design thinking scores than students in other engineering disciplines consistent with the higher design thinking scores of first-year environmental engineering students and given their expectation to help others through their careers which relates to empathy traits that are critical to design thinking.

We tested these hypotheses, using nationally representative samples of first-year and senior engineering students. A total of 2,158 student responses were analyzed for the first-year engineering sample, and 1,853 responses were analyzed for the senior engineering sample. Descriptive statistics were used to characterize design thinkers, and parametric tests were used to compare design thinking measures across sample groups. While this cross-sectional approach cannot provide causal information, it does provide useful insight about the progression of design thinkers in engineering.

Sample and Data Collection

First-year data were collected in two rounds during 2012 using a paper-and-pencil instrument as part of a larger study. The first round randomly sampled 50, 2 and 4-year institutions from a stratified list of institutions from the National Center for Educational Statistics, and the second round specifically targeted 4-year engineering institutions through compilation of a list from the American Society of Engineering Education's online profiles. A total sample size of n = 7,451 was collected from these two rounds where 2,505 students indicated a 3 or 4 on a 0-"Not at all likely" to 4- "Extremely likely" anchored scale of likelihood to choose a particular engineering career pathway. More details on the first-year engineering sample including distribution of respondents based on home ZIP code can be found in (Shealy, et al., 2016) and (Klotz, et al., 2014).

Senior data were collected in one round during the spring semester of 2018 using a paper-and-pencil instrument also as part of a larger study. The sampling frame included a 4-year engineering institutions generated from the National Center for Education Statistics institutional database. A stratified random list was compiled by separating small (< 5,400), medium (5,400-14,800), and large institutions (>14,800) by overall undergraduate enrollment. Engineering department heads were the initial point of contact for each institution. After making contact with the department head, capstone instructors were asked to distribute the survey to their students. A total of 83 capstone courses agreed to participate. No incentives were provided, but capstone instructors were offered access to the raw data in return for their assistance, as approved by IRB procedures. Capstone instructors were mailed the paper surveys and were provided with instructions to distribute the surveys in their senior engineering courses. Sixty-six instructors returned survey responses. A national sample of n = 2,228 senior engineering students was collected. Of those who disclosed their gender in the survey, 77% were male and 23% were female, consistent with the national gender demographics of engineering students who graduate with bachelor's degrees (Yoder, 2018). The representativeness of this sample across the United States is shown in Figure 1. Dots indicate home ZIP codes for at least one respondent (more than one respondent from a ZIP code appears as a single dot).

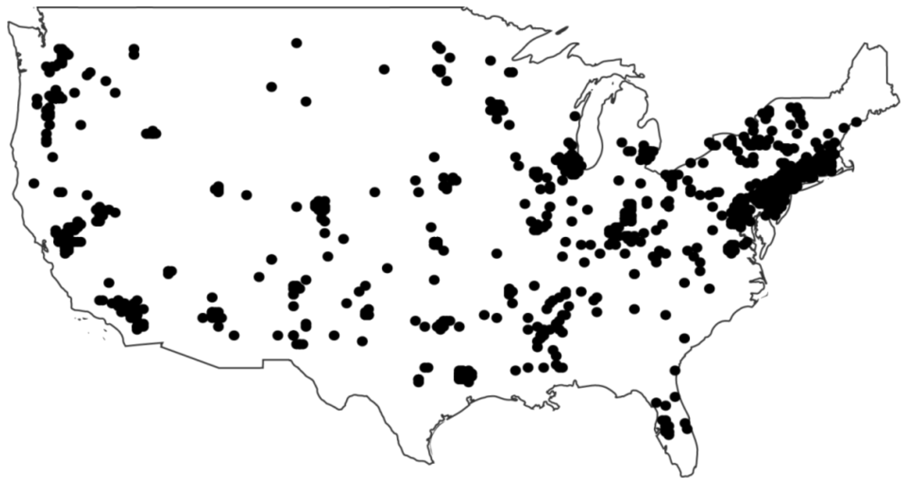

Figure 1. Senior engineering student respondents by home ZIP code.

Data Analysis

Analysis was completed in two phases. First, comparisons were made between the first-year (*n* = 2,158) and senior engineering samples (*n* = 1,853). Respondents that answered less than five of the design thinking items on the nine item scale were eliminated from the data analysis (Table 3). Secondly, comparisons were made within the senior engineering sample between eight engineering disciplines: biomedical (*n* = 55), civil (*n* = 356), chemical (*n* = 436), electrical/computer (*n* = 288), environmental (*n* = 44), industrial (*n* = 165), mechanical (*n* = 469), and materials science (*n* = 36). The sample sizes between disciplines varied widely. However, our sample sizes reasonably represent the distribution of graduating engineering students by discipline where mechanical, civil, electrical/computer, and chemical are the disciplines with the largest graduating classes, and environmental and materials science are some of the smallest graduating classes (Yoder, 2018).

Table 3. Sample sizes and distribution statistics of average design thinking score

	Sample Sizes		Design Thinking Score Statistics		
Education Level	**n collected**	**n analyzed**	**Skewness**	**Excess Kurtosis**	**SD**
Seniors	2,095	1,853	-0.38	1.69	0.456
First-year	2,505	2,158	-0.30	0.28	0.582

Design thinking scores were calculated by averaging the existing data for each student. The scale for each item ranged from "0-Strongly disagree" to "4-Strongly agree." One-way analysis of variance (ANOVA) tests compared design thinking scores between first-year and senior students and compared design thinking scores between the eight engineering disciplines. Assumptions for ANOVA were met including random and independent samples, equal variance between samples ($s_{max}/s_{min} < 2$, where s_{max} is the larger sample variance and s_{min} is the smaller sample variance; Ott & Longnecker, 2001), and approximately normal distribution (Table 3). Multi-factor ANOVA was considered but not chosen because the distribution of gender, a factor that could potentially affect design thinking score (Blizzard, 2013), was comparable across sample groups. Women made up about 25% of each sample, representative of the demographic of engineering bachelor's degree awarded to women (Yoder, 2018). The two sample pooled t-test was also considered for analysis, but was not chosen because the mean squared error in ANOVA is a better predictor of the population standard deviation (σ^2) than sample standard deviation (s_p) used for the t-test (Ott & Longnecker, 2001). Cohen's *d* effect size was calculated in addition to ANOVA to assess the significance of the results.

Descriptive statistical analysis was conducted in addition to ANOVA. The analysis consisted of splitting the combined first-year and senior data into two groups, design thinkers and non-design thinkers. Design thinkers were identified as those with design thinking scores in the upper quartile (score> 3) and non-design thinkers were identified as those with scores in the lowest quartile (score< 2.3). These results are communicated in terms of the percentage of students from each sample (first-year or senior) that fell within one of the two groups (design thinker or non-design thinker). This portion of the analysis was modeled from Blizzard's prior work where design thinking scores of first-year engineering students were analyzed by splitting them into design thinker and non-design thinker groups based on quartiles (Blizzard, 2013).

Validation of the Instrument

Blizzard et al. (2015) conducted exploratory factor analysis (EFA) to develop the design thinking instrument (Table 2). The instrument originally consisted of 18 items, but, through EFA, the number of items was reduced to a 9 item instrument (Blizzard, et al., 2015). Blizzard found through the EFA that the nine item instrument has a five factor structure where each factor corresponds to one of Brown's design thinking traits. Together these design thinking traits cover five domains of design thinking that are a single latent variable, design thinking, based on the theoretical framework. Refer to Table 3 in Blizzard et al. (2015) for the final EFA and for details about the EFA method.

We conducted a confirmatory factor analysis (CFA) using the lavaan package in R (Beaujean, 2014) to determine if the five factor structure held true for the senior engineering sample. The model was evaluated according to several fit indices based on Byrne's suggestions (Byrne, 1994) including Comparative Fit Index (CFI), Tucker Lewis Index (TLI), and root mean square error of approximation (RMSEA) (values less than 0.01, 0.05, and 0.08 indicate excellent, good, and moderate fit, respectively). The chi-square statistic is not a good indicator of model fit for sample sizes greater than 400 (Schumacker & Lomax, 2004), so it was not considered for our analysis. The RMSEA is a better indicator for fit and is less sensitive to changes in sample size (Schumacker & Lomax, 2004). The fit indices for the five factor structure on the senior engineering sample were CFI = 0.966, TLI = 0.932, SRMR=0.036, and RMSEA = 0.063. However, when conducting discriminant validity checks, three of the five factors were highly correlated ($r > 0.85$)- integrative thinking, collaboration, and experimentalism. Based on this correlation, a second CFA was run where integrative thinking, collaboration, and experimentalism were considered to be a single factor. Under this new model structure, the fit indices were CFI = 0.962, TLI = 0.943, SRMR=0.039, and RMSEA = 0.057. Therefore, the fit of the three factor model fits just as well, if not better than, the five factor model. In future studies, items should be added to the instrument in attempts to distinguish integrative thinking, collaboration, and experimentalism as separate factors. We offer suggestions for improvements to the instrument in the Conclusions.

The internal consistency of items was evaluated in addition to validity checks by calculating Chronbach's alpha coefficient. A coefficient of 0.7 or higher is considered acceptable for ability tests and indicates that items may be used interchangeably (Field, Miles, & Field , 2012; Thorndike & Hagen, 1997). Cronbach's alpha was calculated for each of the five sub-scales on the design thinking instrument. The coefficients are as follows: integrative thinking=0.64, optimism=0.33, collaboration=0.66, feedback seeking=0.54, and experimentalism is not available because it's sub-scale only contains one item. Overall, the results for the Cronbach's alpha coefficients do not meet the desired level of 0.7 or higher which may be a result of the small number of items per sub-scale (Field, Miles, & Field , 2012). In order to utilize the existing freshmen data for comparison, we were unable add more items to the instrument for our study. However, recommendations for modification of the instrument in future studies are provided in the Conclusions.

Results

First-year to Senior Comparison

Design thinking scores of the engineering students ranged from 0 to 4 because the scale for each of the nine items ranged from "0-strongly disagree" to "4-strongly agree." The design thinking score distribution for each sample can be visualized with a histogram overlaid by a box-plot in Figure 2. The first-year and senior data are normally distributed with a slightly negative skew, -0.30 and -0.38 respectively. A significant difference between the samples' design thinking scores was found from the one-way ANOVA ($p < 0.0001$). The average design thinking score of senior students (2.59) was significantly lower than first-year (2.80).

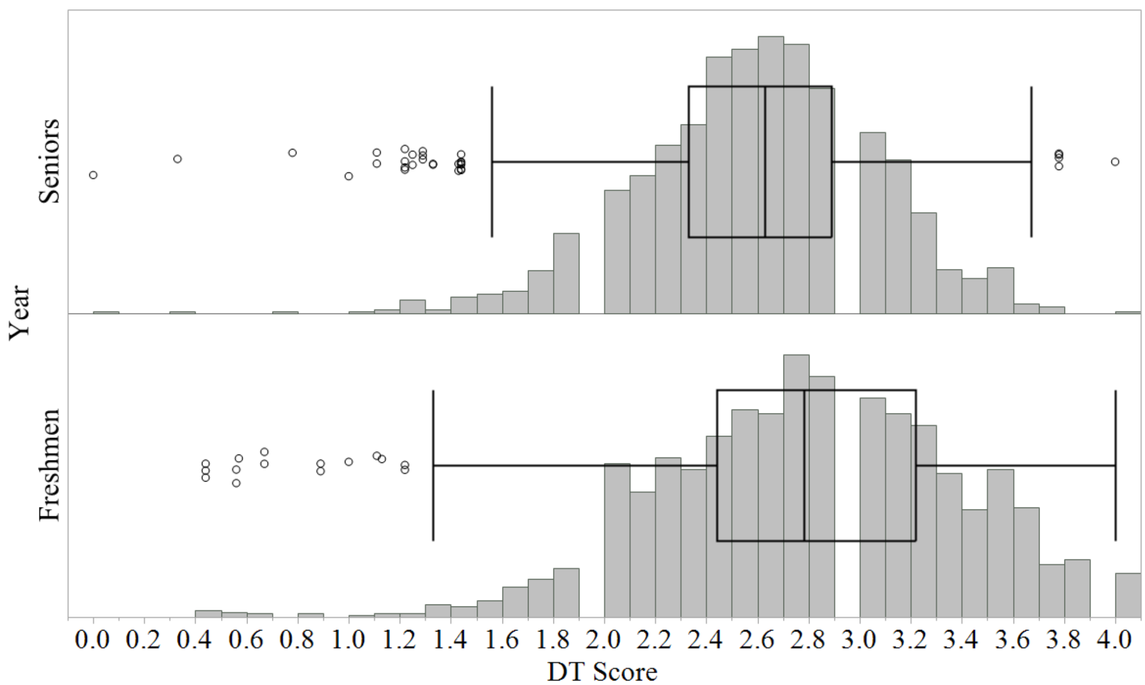

Figure 2. Distribution of design thinking scores for first-year and senior engineering students

Although the design thinking scores were found to be significantly different by ANOVA, it is evident that there is a great deal of overlap between the groups' distribution of scores (Figure 2). For this reason and because the design thinking score is measured on a scale that is unfamiliar to readers, Cohen's *d* was calculated to evaluate the amount of variation between groups. Cohen's *d* effect size was calculated to be 0.40, meaning the groups' means differ by 0.4 standard deviations. According to Cohen, an effect size of 0.4 is considered greater than a small, but less than a medium, effect size (Cohen, 1988). Another way to interpret an effect size of 0.4 is the average senior engineering student would score lower than about 66% of first-year engineering students on the design thinking scale.

To gain additional insight about the differences between design thinking scores, the first-year and senior samples were separated into two groups of "design thinkers" and "non-design thinkers." Design thinkers were classified as students who scored in the upper quartile or 75^{th} percentile (scored higher than 3.0) and non-design thinkers were classified as students who scored in the lower quartile or 25^{th} percentile (scored lower than 2.3) (Blizzard, 2013). Quartile cut-offs were calculated after grouping the first-year and senior design thinking scores. Figure 3 displays the percentages from each sample group that were design thinkers and non-design thinkers. Of the senior engineering students who took the survey, 9.3% were design thinkers and 28.7% were non-design thinkers. This can be compared to first-year engineering students, where 27.9% were design thinkers and 23.4% were non-design thinkers.

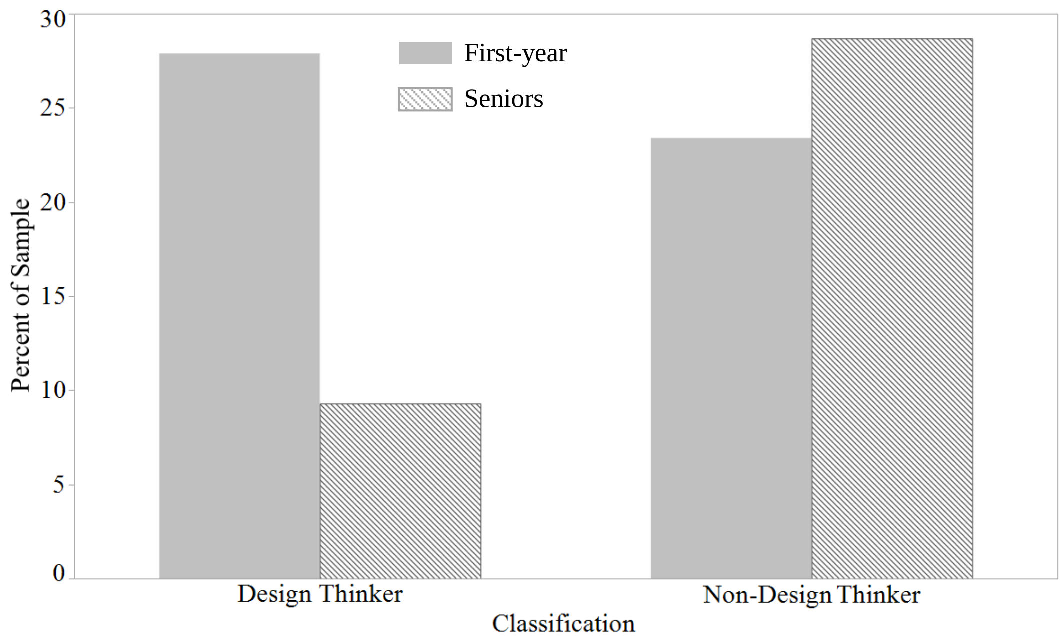

Figure 3. Percentage of samples who were design thinkers and non-design thinkers

In attempts to determine the source of the difference between first-year and senior design thinking scores, the results were broken down by each design thinking trait according to the theoretical framework. Five, two-sample, pooled t-tests were conducted to determine if there were significant differences between the samples for each design thinking trait. Results of the pooled t-tests are given in Table 4. The p-values for integrative thinking, collaboration, experimentalism, and feedback seeking meet Bonferroni correction requirements where p<0.01.

Table 4. Summary comparisons between first-year and senior students

Design Thinking Measures	Aggregated Findings*	Senior Mean	First-year Mean	*p*-value	Effect Size
Design Thinking	S < F	2.59	2.80	<0.0001	0.40
Optimism	S = F	2.82	2.76	0.0220	3.24
Integrative Thinking	S > F	2.90	2.75	<0.0001	8.85
Collaboration	S > F	2.96	2.87	0.0003	5.15
Experimentalism	S < F	2.68	2.76	0.0066	3.85
Feedback Seeking	S < F	1.66	2.83	<0.0001	60.1

*S=senior engineering students, F=first-year engineering students

Sub- Disciplinary Comparison

The design thinking scores of eight engineering disciplines within the senior engineering sample were compared using Wilcoxon's rank-sum test. Wilcoxon's rank-sum test was used instead of ANOVA because the distribution of design thinking scores within the environmental engineering sample was non-normal (skewness= -1.94, kurtosis= 8.06; Table 5). ANOVA is fairly robust to non-normality when sample sizes are equal, but if samples sizes are not equal, it is not robust to violations of homogeneity of variance (Field, Miles, & Field , 2012). In the case of our study, the sample sizes from each discipline are not equal (see Table 5). Therefore, ANOVA could not reliably be used to draw statistical comparisons.

Table 5. Descriptive statistics summary of design thinking score by engineering discipline

Discipline	n	mean	median	skewness	kurtosis	SD
Industrial	63	2.66	2.63	-0.32	1.70	0.48
Materials Sci.	36	2.65	2.63	-0.10	-0.55	0.42
Environmental	44	2.60	2.69	-1.94	8.06	0.58
Chemical	436	2.60	2.63	-0.10	0.06	0.44
Electrical/Comp.	288	2.57	2.63	-0.29	2.25	0.51
Civil	356	2.57	2.63	-0.22	0.13	0.48
Mechanical	469	2.56	2.50	0.11	0.37	0.50
Biomedical	55	2.51	2.50	0.21	-0.75	0.54

Wilcoxon's rank-sum test is a non-parametric test that does not require the assumption of normality and is the non-parametric equivalent of the independent t-test (Field, Miles, & Field , 2012). Seven Wilcoxon's rank-sum tests were completed to compare the average design thinking score of environmental engineering students to the average design thinking score of the other engineering disciplines. The environmental discipline was chosen as the anchor for Wilcoxon's rank-sum test because our hypothesis was that environmental engineering students would have higher design thinking scores than the other disciplines. The results of Wilcoxon's rank-sum tests showed no significant difference in design thinking score between environmental engineering and the other sub-disciplines (Table 6).

Table 6. Results of Wilcoxon's rank-sum test where each discipline was compared to the environmental engineering discipline

Discipline	Difference*	Z statistic	*p*-value
Industrial	0.06	0.041	0.967
Materials Sci.	0.05	0.063	0.950
Chemical	0.00	0.585	0.558
Electrical/Comp.	0.03	0.906	0.365
Civil	0.03	0.854	0.393
Mechanical	0.04	1.213	0.225
Biomedical	0.09	1.268	0.205

*Difference between the mean design thinking score of environmental engineering students and the mean design thinking score of the corresponding discipline

Discussion

Design thinking scores significantly decreased from first-year to senior year of engineering education, and the percentage of design thinkers among first-year students (27.9%) was three times that of senior students (9.3%). While the effect size of the difference in design thinking scores is relatively small (0.4), it is an issue that growth in perceived design thinking ability was not observed. The cause of stagnant design thinking scores could not specifically be evaluated through our descriptive study. However, it is possible that a decrease in the percentage of design thinkers is the result of engineering design courses that often neglect the design thinking approach (Zancul, et al., 2017) combined with highly technical engineering courses that result in decreased creative thinking ability (Sola, Hoekstra, Fiore, & McCauley, 2017).

When examining scores at the trait level, seniors had scores that were significantly lower than the first-year sample for two of the five design thinking traits- experimentalism and feedback seeking- which likely caused their overall design thinking score to be less than that of first-year students. Brown defines experimentalism as "willingness to ask questions and take new approaches to problems." The item that evaluated experimentalism within the design thinking instrument was "When problem solving, I focus on the relationships between issues." A possible explanation for seniors' lower responses on this item is that it does not align well with Brown's definition of experimentalism. The item mentions problem solving, but it does not evaluate willingness to take new approaches or ask questions. The fact that the sub-scale only includes this one item increases the limitation of evaluating experimentalism, since a minimum of three items per scale is preferable to ensure adequate specification of constructs (Raubenheimer, 2004; Godwin, 2016). Items that could be added to improve the experimentalism sub-scale are provided in the Conclusions.

Aside from an instrument flaw, there may be a theoretical explanation for senior student's underperformance on the experimentalism scale. A recent study showed that engineering education fails to improve engineering students' capacity for divergent thinking (Bennetts, Caldwell, Cheeley, & Green, 2017). Divergent thinking is defined as "ignoring old assumptions to produce new ideas" which is similar to Brown's definition of experimentalism "willingness to ask questions and take new approaches to problems." Bennett et al.'s (2017) findings showed no significant difference in ability to generate original, or new, ideas between first-year and senior engineering students. These findings align with another study which compared willingness to take new approaches to problems between first-year and senior students (Atman, Chimka, Bursic, & Nachtmann, 1999). In Atman et al.'s (1999) study, senior engineering students challenged the directions they were given by the experimenter because they did not understand the need to develop multiple alternative solutions for a design problem. The seniors argued only one design was necessary, and they claimed "alternative ideas" could be modifications of the original design (Atman, Chimka, Bursic, & Nachtmann, 1999). The senior engineering students' mindset in this situation directly contradicted with experimentalism because they wanted to modify a previous solution instead of developing a new solution for the task at hand. Given these prior studies which provide reason for a decreases in experimentalism, future quantitative studies should be carried out with the modified experimentalism sub-scale (see Conclusions) to determine if, in fact, seniors are worse at experimentalism than first-year students.

Feedback seeking was another trait where senior engineering students scored lower than first-year engineering students. Although not perfectly aligned with Brown's framework, the feedback seeking scale does provide some insight on Brown's empathy trait. For example, when discussing empathy in the context of design thinking, it is a form of knowledge construction (Koppen & Meinel, 2015) that leads to holistic solutions by seeking feedback from the user. Designing with the user in mind, which requires empathic concern as well as a desire to seek feedback from the user, is becoming a topic of interest within the engineering curriculum. However, a prior study showed that a user-centered way of thinking does not come naturally to engineering students and is something that must be explicitly addressed when talking about design (Zoltowski, Oakes, & Cardella, 2012). Because a nationally representative sample of senior students scored significantly lower on the feedback seeking scale by a very large effect size (Cohen's *d*= 60.1), our results may suggest that there is not enough concentration on user-centered design within the engineering education curriculum.

Conclusions

Our study presents evidence to suggest that design thinking decreases from first-year to senior year, specifically for experimentalism and feedback seeking traits. Further, design thinking scores among senior students are stable across eight engineering disciplines (industrial, materials science, environmental, mechanical, biomedical, electrical/computer, and chemical). Design thinking is an excellent approach to solving some of the most complex, open-ended, and ill-defined problems within the real-world (Blizzard, 2013), so engineering educators should be concerned that growth in perceived design thinking ability was not observed from freshmen to senior year. Action must be taken to increase the value of design thinking within the engineering curriculum because of the value employers and industry leaders place on hiring design thinkers (Brown, 2008; Dym, Agogino, Eris, Frey, & Leifer, 2005).

Implications

Specific areas where engineering curriculum could be improved to address shortcomings in senior students' design thinking include communicating the value of user-centered design (Zoltowski, Oakes, & Cardella, 2012) and encouraging divergent thinking (Bennetts, Caldwell, Cheeley, & Green, 2017) when solving problems. Greater concentration on user-centered design and divergent thinking may improve senior students' tendency to seek feedback and increase comfort with experimentalism (Daly, Mosyjowski, & Seifert, 2014), respectively. McKilligan et al. (2017) have outlined a plan to implement the design thinking approach within a traditional electrical and computer engineering department. Their approach includes generating a diverse range of ideas through experimentalism and seeking feedback from the user. McKilligan et al.'s study is currently in the experimental stage, but their ideas can serve as a roadmap for other engineering departments to implement the design thinking approach into their programs.

Limitations

The six-year time span between collections of the first-year and senior data samples was one limitation of this study. However, the cross-sectional method was appropriate for our research because_(need citation)_. Future studies could be conducted within the next couple of years to collect a new first-year student data sample.

A larger limitation associated with our descriptive study is that the samples had to self-identify their ability. However, our intentions with this study were to take a nationally representative look at design thinking of engineering students and utilizing empirical methods would not have allowed us to do so. Future researchers could empirically compare design thinking ability between freshmen and seniors by observing their actual performance on a design task.

The largest limitation of our study was inability to make improvements to Blizzard et al.'s (2015) design thinking instrument. We were unable to make improvements because we wanted to make an equal comparison with the existing first-year data. However, the results of our study, including the confirmatory factor analysis, can help inform improvements for future studies. We offer some suggestions for improvement in the following section.

Future Studies

In order to contribute to future quantitative studies on design thinking, we would like to provide recommendations for revising the design thinking instrument, including the addition of items. The recommendations are provided in Table 7; they are based on the researchers' expertise from utilizing the instrument and are recommended with the intention of improving the instrument to be a better fit of Brown's theoretical framework. The items recommended for addition to the instrument are italicized.

Table 7. *Revised Design Thinking Instrument for Future Study*

Design Thinking Characteristics	Survey Questions
Feedback Seeking- willingness to seek input from others to make decisions and change directions.	I seek input from those with a different perspective from me.
	~~I seek feedback and suggestions for personal improvement.~~
	I think seeking input from the user is an important part of the design process.
	I understand the value of seeking feedback while my work is in progress.
Integrative Thinking- ability to analyze holistically to develop novel solutions.	I analyze projects broadly to find a solution that will have the greatest impact.
	I identify relationships between topics from different courses.
	I think about how solutions can be integrated into a larger context.
	I like to narrow my focus when deriving solutions to ensure I am addressing the problem at hand.
Optimism- refusal to back down from challenging problems.	I can personally contribute to a sustainable future.
	Nothing I can do will make things better in other places on the planet.
	I view challenges as opportunities not as threats.
	I find it difficult to remain motivated when a problem is challenging.
Experimentalism- willingness to ask questions and take new approaches to problem solving.	When problem solving, I focus on the relationships between issues.
	I ask questions when finding new approaches to problem solving.
	Generating ideas is an important part of the design process.
Collaboration- ability to work with many disciplines and willingness to experience other fields.	I hope to gain general knowledge across multiple fields.
	I often learn from my classmates.
	I value the perspectives of my team mates when working in a group.
	It find it difficult to work collaboratively.

The items added to the feedback seeking sub-scale are targeted towards measuring respondents' tendencies to seek feedback from the user while their work is still in progress. The new items focus on feedback seeking in terms of the user because of the implications of this study which call for increased incorporation of user-centered design into the engineering curriculum. We also recommend removing the item "I seek feedback and suggestions for personal improvement" because the focus on personal improvement may be subject to self- selection bias.

The items added to the integrative thinking sub-scale are focused on identifying the respondents' tendency to analyze holistically. One item is a positive predictor of the ability to analyze holistically and the other item is a negative predictor. The existing items of the sub- scale may remain unrevised as they also target measurement of holistic analysis.

The items added to the optimism sub-scale are intended to evaluate optimism in broader terms. The original instrument evaluated optimism in relation to sustainability whereas the new items seek to evaluate optimism on a broader scale. One item is a positive predictor and the other is a negative predictor of optimism. Evaluation of optimism in broader terms will make the scale more resilient for future cross-sectional studies, since environmental perspectives have the potential to evolve and change over time.

The items added to the experimentalism sub-scale are intended to better align the scale with Brown's definition of experimentalism. The existing item addresses problem solving, but does not address willingness to take new approaches to problem solving. Therefore, an item was added to address this shortcoming. An item which refers to generating ideas was also added based on the connection that was made between divergent thinking and experimentalism in this study.

The items added to the collaboration sub-scale are intended to measure collaboration more directly. The existing items evaluate collaboration indirectly by inquiring about tendencies that can contribute to a collaborative mindset. The recommended items include a positive predictor and a negative predictor that are targeted towards a more direct measurement of collaboration.

From the Cronbach's alpha results, it was clear that more items need to be added to the instrument since only nine items represent five separate sub-scales. We hope that future researchers find our recommendations for modification of the instrument useful, and we hope that engineering educators find our recommendations for incorporation of feedback seeking and experimentalism into the classroom helpful.

References

Atman, C., Chimka, J., Bursic, K., & Nachtmann, H. (1999). A Comparison of Freshman and Senior Engineering Design Processes. *Design Studios*, 131-152.

Bazylak, J., & Wild, P. (2007). Best practices review of first-year engineering design education. Winnipeg: Canadian Engineering Education Association.

Beaujean, A. A. (2014). *Latent Variable Modeling Using R: A Step-by-Step Guide.* New York, NY: Taylor & Francis.

Beckman, S. L., & Barry, M. (2007). Innovation as a Learning Process: Embedding Design Thinking. *California Management Review*, 25-56.

Bennetts, C., Caldwell, B., Cheeley, A., & Green, M. (2017). Comparing Facets of Divergent Thinking in Engineering Freshmen and Upperclassmen. *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.* Cleveland: ASME.

Blizzard, J. (2013). *Design Thinkers Can Save the World: How Understanding their Interests, Goals, and Motivations can Inform Engineering Educators.*

Blizzard, J., Klotz, L., Potvin, G., Hazari, Z., Cribbs, J., & Godwin, A. (2015). Using Survey Questions to Identify and Learn more About Those who Exhibit Design Thinking Traits. *Design Studies*, 92-110.

Brown, T. (2008). Design Thinking. *Harvard Business Review*.

Buchanan, R. (1992). Wicked Problems in Design Thinking . *Design Issues*, 5-21.

Byrne, B. M. (1994). *Structural Equation Modeling with EQS and EQS/Windows: Basic Concepts, Applications, and Programming.* SAGE Publications Inc.

Cohen, J. (1988). The Concepts of Power Analysis. In *Statistical Power Analysis for the Behavioral Sciences* (pp. 1-17). New York, NY: Lawrence Erlbaum Associates.

Cropley, D. H. (2015). Embedding Creativity in Engineering Education. In *Creativity in Engineering* (pp. 257-289). Elsevier Inc.

Daly, S., Mosyjowski, E., & Seifert, C. (2014). Teaching Creativity in Engineering Courses. *Journal of Engineering Education*, 417-442.

Davis, M. (1980). A multidimensional approach to individual differences in empathy. *JSAS Catalog of Selected Documents in Psychology*.

Dym, C., Agogino, A., Eris, O., Frey, D., & Leifer, L. (2005, January). Engineering Design Thinking, Teaching, and Learning. *Journal of Engineering Education*, 103-120.

Ercan, F., Sale, D., & Kristian, N. (2016). Innovative Curriculum to Enhance the Learning Experience of Electrical and Mechanical Engineering Students. *International Journal of Engineering Pedagogy*, 37-44.

Foley, S., & Kazerounian, K. (2007). Barriers to Creativity in Engineering Education: A Study of Instructors and Students Perceptions. *ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 539-555). Las Vegas: ASME.

Froyd, J., Wankat, P., & Smith, K. (2012). Five Major Shifts in 100 Years of Engineering Education. *IEEE. 100*, pp. 1344-1360. IEEE.

Godfrey, E. (2014). Understanding Disciplinary Cultures. In A. Johri, & B. Olds, *Cambridge Handbook of Engineering Education* (pp. 437-456). Cambridge University Press.

Godwin, A. (2016). The Development of a Measure of Engineering Identity. *Jazzed about Engineering Education.* New Orleans, LA: American Society for Engineering Education.

Howard, T., Culley, S., & Dekonick, E. (2008). Describing the Creative Design Process by the Integration of Engineering Design and Cognitive Psychology Literature. *Design Studies*, 160-180.

Howe, S. (2010). Where Are We Now? Statistics on Capstone Courses Nationwide. *Advances in Engineering Education*.

Klotz, L., Potvin, G., Godwin, A., Cribbs, J., Hazari, Z., & Barclay, N. (2014). Sustainability as a Route to Broadening Participation in Engineering. *Journal of Engineering Education, 103*, 137-153.

Koppen, E., & Meinel, C. (2015). Empathy via Design Thinking: Creation of Sense and Knowledge. *Design Thinking Research*, pp. 15-28.

Leiserowitz, A., Maibach, E., Roser-Renouf, C., Rosenthal, S., Cutler, M., & Kotcher, J. (2018). *Climate Change in the American Mind.* George Mason University Center for Climate Change Communication. Yale Program on Climate Change Communication.

Levine, D., Agogino, A., & Lesniewski, M. (2016). Design Thinking in Development Engineering. *International Jounral of Engineering Education*, 1396-1406.

McKilligan, S., Fila, N., Rover, D., & Mina, M. (2017). Design Thinking as a catalyst for changing teaching and learning practices in engineering. *Frontiers in Education Conference.* Indianapolis: IEEE.

Ott, R., & Longnecker, M. (2001). *An Introduction to Statistical Methods and Data Analysis.* Pacific Grove: Thomson Learning Inc.

Potvin, G., Hazari, Z., Klotz, L., Godwin, A., Lock, R., Cribbs, J., & Barclay, N. (2013). Disciplinary Differences in Engineering Student's Aspirations and Self Perceptions. *ASEE Annual Conference & Exposition.* Atlanta: American Society for Engineering Education.

Raubenheimer, J. (2004). An Item Selection Procedure to Maximise Scale Reliability and Validity. *Journal of Industrial Psychology*, *30*(4), 59-64.

Rowe, P. G. (1986). *Design Thinking.* Cambridge, MA: The MIT Press.

Schaar, R. Y., Rains, J. K., & Jacobson, M. C. (2015). Jump-Starting Biomedical Design Education in the Sophomore Year: A Human Centered Approach. *Open.* Washington: VentureWell.

Schumacker, R., & Lomax, R. (2004). *A Beginner's Guide to Structural Equation Modeling.* Mahwah, NJ: Lawrence Erlbaum Associates.

Shealy, T., Valdes-Vasquez, R., Klotz, L., Potvin, G., Godwin, A., Cribbs, J., & Hazari, Z. (2016). Career Outcome Expectations Related to Sustainability among Students Intending to Major in Civil Engineering. *Journal of Professional Issues, 142*.

Sola, E., Hoekstra, R., Fiore, S., & McCauley, P. (2017, July). An Investigation of the State of Creativity and Critical Thinking in Engineering Undergraduates. *Creative Education*, 1495-1522.

Sternberg, R. (1998). *Handbook of Creativity.* Cambridge University Press.

Strimel, G. J., & Kelley, T. R. (2017). Establishing Core Undergraduate Design & Innovation Curriculum:Reaching New Audiences. *Mississippi Valley Technology Teacher Education Conference.* Sr. Louis.

Treffinger, D., Young, G., Shelby, E., & Shepardson, C. (2002). *Assessing creativity: A guide for educators.* Sarasota: The National Research Center on the Gifted and Talented.

Yoder, B. L. (2018). *Engineering By the Numbers.* American Society for Engineering Education.

Zancul, E. D., Durao, L. F., Lopes, R. D., Nakano, D., Blikstein, P., Majzoub, G., & Dalmon, D. (2017). An Empirical Study on Design-Based vs. Traditional Approaches in Capstone Courses in Engineering Education. *International Journal of Engineering Education*, 1543-1560.

Zoltowski, C. B., Oakes, W. C., & Cardella, M. E. (2012). Students' Ways of Experiencing Human-Centered Design. *Journal of Engineering Education*, 28-59.

Journal Paper:

Who are Better Design Thinkers’ Engineers or Architects? Measuring the Effects of Design Education on Engineering and Architecture Students

Intended Outlet for Publication:
Design Studies

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Abstract

Comparisons were made between the design thinking abilities of engineering and architecture students in their final year of undergraduate studies. Design thinking ability was evaluated through a survey that was distributed to engineering and architecture students enrolled in four-year institutions across the United States. Statistical analyses, specifically the Analysis of Variance (ANOVA) test, was conducted to make comparisons between the architecture (n=336) and engineering samples (n=1,853). There was a significant difference in design thinking ability between the groups where architecture students scored higher than engineering students. 75% of architecture students were design thinkers compared to only 14% of engineering students. These results have important implications for engineering educators.

Keywords: design thinking, design education, architectural design, engineering design

Introduction

The best design work in both the architecture and engineering disciplines is able to "creatively meet the needs of its users, satisfy technical requirements, and achieve beauty" (Little & Cardenas, 2001, p. 309). Yet, the disciplines have distinctively different approaches to meet these objectives. Starting at the end of the 18th century, architects and engineers took on separate job titles, as a result of the Industrial Revolution, which led to conflict in their professional and academic worlds. Conflicts emerged between the disciplines because of a perceived tension between creativity and technical fundamentals (Little & Cardenas, 2001). Despite these conflicts, architecture and engineering disciplines have influence within the same realm of design.

Design is explored broadly in four topic areas: 1) symbolic and visual communications, 2) material objects, 3) activities and organized services, and 4) complex living, working, playing, and learning systems or environments (Buchanan, 1992). The broad area of "complex living, working, playing, and learning systems or environments," traditionally includes the design disciplines of engineering and architecture (Buchanan, 1992, p.10). This area explores "the role of design in sustaining, developing, and integrating human beings into broader ecological and cultural environments, shaping these environments when desirable and possible, or adapting to them when necessary," (Buchanan, 1992, p. 10). Although the architecture and engineering disciplines belong to the same topic area of design, their educational curriculums are vastly different. Architecture educators struggle to teach a balance between creativity and rationality in the design studio (Bashier, 2014) while engineering educators struggle to encourage creativity in the classroom (Daly, Mosyjowski, & Seifert, 2014). The study in this article examines differences in design thinking ability between the two disciplines and frames these differences in terms of their respective educational curriculums, offering recommendations for educators.

Within both disciplines, educators utilize design thinking as an approach to design pedagogy which provides a basis for comparison between the groups. Several definitions of design thinking exist, but Tim Brown, a design educator and practitioner, defined design thinking in broad terms that encompass both the architecture and engineering design disciplines (Blizzard, et al., 2015). Brown defines design thinking as "a human-centered, creative, iterative, and practical approach to finding the best ideas and ultimate solutions to the world's greatest problems" (Brown, 2008, p. 92). He also characterizes certain traits of design thinkers including: a willingness to ask questions and take new approaches to problem solving (experimentalism); an ability to analyze holistically to develop novel solutions (integrative thinking); an ability to adopt the psychological viewpoint of others in everyday life (empathy); an ability to work with many disciplines (collaboration); and refusal to back down from challenging problems (optimism) (Brown, 2008). A design thinking survey was developed based on Brown's design thinking traits (Blizzard, et al., 2015) and was utilized to quantitatively compare design thinking between national samples of engineering (n=2,095) and architecture students (n=336) in this study. The following section provides a detailed review of differences in education that could lead to differences in design thinking capability between architecture and engineering students.

1 Background

The architecture field has a rich history of valuing and teaching skills relevant to design thinking while fields like engineering have not truly integrated them into their education programs (Kumar & Hsiao, 2007; Mohan, Merle, Jackson, Lannin, & Nair, 2009; Darabi, Douzali, Karim, Harford, & Johnson, 2017). In this section, architecture and engineering design education are compared based on Brown's design thinking traits. The review begins with a comparison of design education between architecture and engineering disciplines and then explains hurdles for incorporating design thinking into engineering design education.

1.1 Comparisons of Design Education across Architecture and Engineering Disciplines

The American Institute of Architecture considers the design thinking process as the most critical aspect of design studio education (Bashier, 2014). Studio education is traditionally viewed as a pedagogical approach for "artistic" disciplines, like architecture, not engineering (Little & Cardenas, 2001). Studio education typically includes (1) semester-length projects with a complex/open-ended nature; (2) design solutions which undergo multiple and rapid iterations; (3) frequent informal and formal critique of work-in-progress by peers and instructors; (4) conversations to simultaneously address heterogeneous issues; (5) situating designs within the big picture of previous works; (6) faculty guidance on how to impose constraints to find a satisfactory solution; and (7) appropriate use of multiple design media to support design activities and improve skill and insight (Kuhn, 1999).

In a survey of five architecture programs, traditional studio education made up one-third of their design curricula. In the same survey, five mechanical engineering programs stated that studio education was nonexistent in their curriculum (Nix, Lemke, Arlitt, & Stone, 2016). Some 21st century approaches in engineering education have experimented with studio pedagogy, but it is rarely incorporated. The definition of studio pedagogy within engineering education ranges widely (Little & Cardenas, 2001; Connor, Karmokar, & Whittington, 2015; Ercan, Sale, & Kristian, 2016) from an isolated environment where students teach themselves with guided computer exercises to an interactive environment where a mentor encourages and comments on ongoing work (Little & Cardenas, 2001). The latter end of this scope is conducive with traditional architecture studio design approaches. Comparing Kuhn's seven characteristics of traditional architecture studio pedagogy to traditional engineering design courses reveals a few differences that make architecture education stand out with a higher potential for design thinking: 1) architecture studio courses prioritize prototyping; 2) architecture studio courses emphasize the importance of informal critique on works-in-progress; and 3) architecture education encourages creative thinking. The following paragraphs further address each of these differences.

The first difference is the significance that architecture studio attributes to prototyping or in Kuhn's words, "design[ing] solutions which undergo multiple and rapid iterations," (Kuhn, 1999). In contrast to architecture courses, only 37% of respondents from a survey of 400 engineering design courses indicated that prototyping was a topic taught in their course (Howe, 2010). Prototypes are essential to the design thinking approach because, as defined by Brown, "design thinking is a human-centered, iterative approach," (Brown, 2008). Ability to understand the needs of the user and utilize iterative design as a means to meet user needs can be characterized as a significant component of empathy, one of Brown's design thinking characteristics. Therefore, architecture students may have a higher design thinking ability than engineering students, since prototyping is central to their education experience within studio courses.

Second, architecture and engineering design courses differ in the frequency of both formal and informal critique on works-in-progress by peers and instructors. 66% of engineering students in capstone design courses said finding time to work on their design project was either entirely or partially there responsibility, meaning 66% did not have a class period dedicated purely to project work (Howe, 2010). This format does not lend itself to instructor critique on works-in-progress. Although engineering design courses generally involve presentations of progress, they are infrequent and predominately formal. 92% of engineering students have formal final presentations while only 25% had more than one formal interim presentation (Howe, 2010). Perhaps the most shocking statistic is that more than half (55%) of capstone engineering students said their designs were never reviewed (Howe, 2010). This shortcoming of engineering design education may be detrimental to engineering students' design thinking ability. Without having their designs challenged through review and critique, engineering students are not given the opportunity for divergent thinking through ideation, which is a crucial component of experimentalism, one of Brown's design thinking characteristics (Brown, 2008). In addition, little time for project work during class does not encourage collaboration between peers nor instructor.

A third key difference between architecture and engineering design education is comfort with the concept of creativity, specifically attention to divergent thinking in pedagogical approaches.

Architecture studio courses highly encourage Treffinger et al.'s creative thinking category "generation of ideas," in other words divergent thinking, (Treffinger, Young, Shelby, & Shepardson, 2002) with project assignments that are complex and open-ended (Kuhn, 1999). Generation of ideas or divergent inquiry allows for conceptual thinking where answers are not required to have truth value, in other words answers are not always verifiable (Dym, Agogino, Eris, Frey, & Leifer, 2005). This way of thinking directly conflicts with principles at the core of an engineering science approach. It would be unacceptable for an engineering student to respond to a final exam question in an engineering science course by providing multiple concepts with no truth value (Dym, Agogino, Eris, Frey, & Leifer, 2005). However, these types of responses are often encouraged within architecture studio courses to support design of innovative, artistic forms (Bashier, 2014). Convergent thinking is well represented in engineering design courses (McKilligan, Fila, Rover, & Mina, 2017), but instruction on generating ideas and openness to exploring ideas is less evident (Daly, Mosyjowski, & Seifert, 2014). Shortcomings of creative thinking and divergent thinking engineering education might be attributed to a lack of value placed on creative skill development (Cropley, 2015).

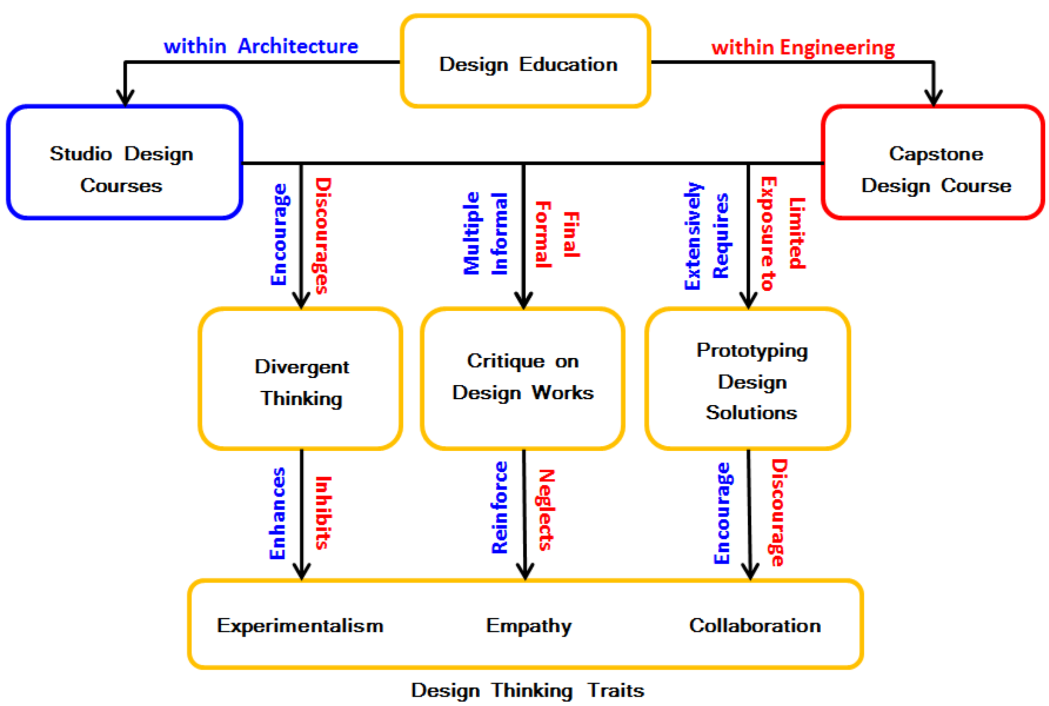

Figure 4. Summary of Differences between Architecture and Engineering Disciplines that Effect Design Thinking

1.2 Hurdles for Incorporating Design Thinking in Engineering Design Education

1.2.1 Shortcomings of creative thinking development in engineering design education

There is a lack of value attributed to creative skill development in engineering education (Cropley, 2015). Cropley, an expert on the incorporation of creativity in the engineering field, has identified three barriers to teaching creativity in engineering education: 1) overspecialization and narrow focus on technical content, 2) pseudo-expertise or teaching purely focused in factual knowledge rather than adaptive expertise, and 3) engineering faculty's lack of knowledge where the focus is on "what" and "can" rather than "how" and "why," (Cropley, 2015). Across fields, engineering has the greatest room for improvement in supporting creative skill development (Foley & Kazerounian, 2007). In recent years, the National Academy of Engineers has taken note of this shortcoming and recognizes the need to improve engineering design education. As a result, they proposed a 2020 initiative calling for creativity in engineering graduates (Bairaktarova, 2017). Current pedagogy decreases engineering students' creativity from freshmen to senior year (Sola, Hoekstra, Fiore, & McCauley, 2017), but it is possible to improve creative ability by taking small steps in creativity training (Sola, Hoekstra, Fiore, & McCauley, 2017). Creative thinking influences design thinking, so engineering pedagogy may need to shift in order to improve the design thinking ability of engineering graduates (Bairaktarova, 2017).

1.2.2 Shortcomings of divergent thinking development in engineering design education

In addition to falling short on creative thinking development, engineering education fails to improve engineering students' capacity for divergent thinking (Bennetts, Caldwell, Cheeley, & Green, 2017). When comparing divergent thinking between freshman and senior engineering students, a study found that both groups produced their most original ideas in familiar ideation tasks as compared to unfamiliar tasks (Bennetts, Caldwell, Cheeley, & Green, 2017). This finding is contrary to the definition of divergent thinking, "ignoring old assumptions to produce new ideas" (Bennetts, Caldwell, Cheeley, & Green, 2017, p. 1), and shows there is no significant difference in ability to generate original ideas between freshmen and senior engineering students. These results align with another study which compared the design process approach of freshmen and engineering students (Atman, Chimka, Bursic, & Nachtmann, 1999). In the study, freshmen accepted the given description of the design process while seniors challenged directions given to develop alternative solutions. The seniors argued only one design was necessary, and they claimed “alternative ideas” could be modifications of the original design. A similar phenomenon of “fixation” has been observed more recently among engineering designers in professional practice (Crilly, 2015). In a world that relies on engineers to solve the complex Grand Challenges of the 21st century, it is problematic that engineering education is not preparing future engineers to generate original ideas when given an unfamiliar task which is paramount to the experimentalism trait of a design thinking mindset.

1.2.3 Shortcomings of engineering design education as a barrier to design thinking of engineering graduates

A decrease in creative ability (Sola, Hoekstra, Fiore, & McCauley, 2017) and stagnation of divergent thinking over the course of an engineering education (Bennetts, Caldwell, Cheeley, & Green, 2017) are reasons to believe engineering pedagogy is falling short of producing advanced design thinkers. A possible cause of these shortcomings is lack of faculty commitment to design pedagogy that incorporates creativity training and divergent thinking assessment (McKilligan, Fila, Rover, & Mina, 2017; Sola, Hoekstra, Fiore, & McCauley, 2017; Dym, Agogino, Eris, Frey, & Leifer, 2005). Engineering educators may need to look towards the humanities for guidance (Bairaktarova, 2017), especially the discipline of architecture whose educators consider the design thinking process as the most critical aspect of design education (Bashier, 2014).

2 Questions and Hypotheses

The research questions that guided this study include: 1) what differences exist in self- reported design thinking ability between senior engineering and senior architecture students; and 2) are there specific traits of design thinking where senior architecture students and senior engineering students differ in their perceived abilities? Answering these questions fills a gap in the literature for a quantitative comparison of design thinking ability between architecture and engineering students. The hypotheses of this study that correspond with the research questions include: 1) architecture students have a higher perceived design thinking ability than engineering students during their final year of undergraduate studies; and 2) architecture students outperform engineering students in the experimentalism and collaborative design thinking traits, based on Kuhn's principles of architecture studio education.

3 Survey Development

The survey to measure design thinking traits between architecture and engineering students contained two major components, both developed from previous studies: 1) a design thinking scale (Blizzard, et al., 2015), and 2) an empathy scale (Davis, 1980). The empathy scale was added in attempts to improve the design thinking scale. Explanations of the scales are provided in this section along with an explanation of methods used for their validation.

3.1 Design Thinking Scale

In 2012, a survey titled Sustainability and Gender in Engineering (SaGE) was administered nationwide to 7,451 freshmen collegiate students from 59 U.S. institutions (Shealy, et al., 2016). The survey included a nine item design thinking instrument (Table 8) based on Brown's five design thinking traits: collaboration, integrative thinking, experimentalism, optimism, and empathy (Brown, 2008). The article, "Using survey questions to identify and learn more about those who exhibit design thinking traits," was published in the *Design Studies* Journal in 2015 detailing the development of the scale (Blizzard, et al., 2015).

Table 8. Design thinking instrument

Design Thinking Traits	Survey Questions
Feedback Seekers- they ask questions and look for input from others to make decisions and change directions.	I seek input from those with a different perspective from me.
	I seek feedback and suggestions for personal improvement.
Integrative Thinking- they can analyze at a detailed and holistic level to develop novel solutions.	I analyze projects broadly to find a solution that will have the greatest impact.
	I identify relationships between topics from different courses.
Optimism- they don't back down from challenging problems	I can personally contribute to a sustainable future.
	Nothing I can do will make things better in other places on the planet.
Experimentalism- they ask questions and take new approaches to problem solving.	When problem solving, I focus on the relationships between issues.
	I hope to gain general knowledge across multiple fields.

Collaboration- they work with many different disciplines and often have experiences in more than just one field.	I often learn from my classmates.

Note. Design thinking traits were taken from Brown (2008) and survey questions were taken from Blizzard (2015).

The items “I seek input from those with a different perspective from me” and “I seek feedback and suggestions for personal improvement” described a feedback seeking variable which is not included within Brown’s design thinking traits (Blizzard, et al., 2015). To better compare the empathy design thinking trait between architecture and engineering students, a perspective taking empathy scale was added to the survey instrument (see the following section). The items which evaluate the other four design thinking traits (collaboration, integrative thinking, experimentalism, and optimism) were unchanged for use in this study.

3.2 Perspective Taking Empathy Scale

For this study, seven survey questions were added to better measure empathy as a design thinking trait. These questions were taken from the Interpersonal Reactivity Index (IRI), a multidimensional instrument for evaluation of empathy (Davis, 1980). The instrument contains four seven-item subscales: perspective taking, empathic concern, personal distress, and fantasy scale. The perspective taking subscale measures the reported tendency to spontaneously adopt the psychological point of view of others in everyday life (Davis, 1980)- a necessary strength for design thinking (Koppen & Meinel, 2015). Therefore, the questions to evaluate empathy were drawn from the perspective taking subscale of the IRI (Table 9).

Table 9. Design thinking empathy questions (Davis 1980)

Perspective Taking Subscale of Interpersonal Reactivity Index
1. I sometimes find it difficult to see things from the other person’s point of view.
2. I try to look at everybody’s side of a disagreement before I make a decision.
3. When I’m upset at someone, I usually try to “put myself in his shoes for a while.
4. Before criticizing somebody, I try to imagine how I would feel if I were in their place.
5. I believe there are two sides to every question and try to look at them both.

6.	I sometimes try to understand my friends better by imagining how things look from their perspective
7.	If I’m sure I’m right about something, I don’t waste much time listening to other people’s arguments.

3.3 Validation of the Survey Instruments

When conducting research with a survey instrument, it is important to determine if the survey questions appropriately measure the intended variable for the target sample group. This section will describe the techniques utilized to validate the survey instrument or, in other words, to ensure that the design thinking and empathy scales were appropriate measures for the samples of interest.

3.3.1 Exploratory Factor Analysis

Exploratory factor analysis (EFA) is a technique commonly used for development of survey instruments. When researchers develop survey instruments, EFA is used to mathematically determine the number of factors that a survey scale measures for some sample population. Each factor predicted through the EFA is indicative of a latent variable. The latent variables are inferred by the researcher on the basis of a theoretical framework. The design thinking scale utilized for this study was developed based on the theoretical framework set forth by Brown’s design thinking traits (Brown, 2008). Prior researchers performed an EFA on this design thinking scale. Their procedure and results are described in great detail within a *Design Studies* article published in 2015 (Blizzard, et al., 2015). In summary, they found that the design thinking scale measured five factors when applied to a freshmen engineering data sample.

The five factors shown through the EFA were indicative of each of Brown’s five design thinking traits (Brown, 2008), with the exception of empathy. Empathy was the exception because the researchers did not believe any of the factors could adequately measure empathy based on its definition in the theoretical framework. Instead, it was inferred that this extra factor measured a “feedback seeking” latent variable. These distinctions were made under the discretion of the researchers and based on their previously defined theoretical framework which originated with Brown’s definition of design thinking (Brown, 2008). In attempts to better measure the empathy trait, the perspective taking scale was added, a subscale of the larger Interpersonal Reactivity

Index (IRI). The psychology researchers who developed the IRI conducted an EFA which showed that the seven questions on the perspective taking scale measure just one factor, perspective taking (Davis, 1980).

3.3.2 Confirmatory Factor Analysis

Confirmatory factor analysis (CFA) is a technique commonly used for the validation of survey instruments. A CFA is typically performed based on the results of an EFA to determine if the factor structure determined by the EFA holds true when the survey instrument is applied to a different data sample. CFA was conducted here to ensure that the design thinking and empathy scales were appropriate for measurements within the new data samples. In other words, Blizzard et al.'s (2015) design thinking instrument was originally developed for freshmen engineers and Davis's empathy scale was originally developed for psychology students The CFA was carried out to ensure that the two scales could be reliably implemented within the populations of interest for this study, senior architecture and senior engineering students.

CFA for the design thinking scale was conducted based on Blizzard et al.'s five factor structure, and CFA for the empathy scale was conducted based on the one factor structure of the perspective taking subscale (Davis, 1980). Once CFA was performed, several fit indices were evaluated to determine if the factor structure was a good fit including Comparative Fit Index (CFI, acceptable values above 0.9), Tucker Lewis Index (TLI, acceptable values above 0.9), and root mean square error of approximation (RMSEA, values less than 0.01, 0.05, and 0.08 indicate excellent, good, and moderate fit, respectively) (Byrne, 1994). These fit indices are provided in Table 10 for the sample groups within each survey instrument.

Table 10. Confirmatory factor analysis fit indices

	Design Thinking Scale			**Empathy Scale**		
	CFI	TLI	RMSEA	CFI	TLI	RMSEA
Architecture	0.974	0.948	0.05	0.907	0.860	0.100
Engineering	0.966	0.932	0.06	0.896	0.845	0.122

The design thinking five factor model was a good fit for the architecture student sample (RMSEA=0.05), and it was a moderate fit for the engineering student sample (RMSEA=0.06).

However, the one factor model for measurement of empathy on the perspective taking scale did not appropriately fit either of the sample groups. In other words, Davis's empathy scale, originally developed for psychology students, does not adequately measure empathy of the sampled engineering and architecture students in this study. Therefore, it is not reasonable to make conclusions in this study based on results from the empathy scale. The results presented in section 4 only address comparisons from the design thinking scale. Rich knowledge can still be attained about differences in design thinking ability between the disciplines even though empathy cannot be reliably represented.

4 Sample and Methodology

Quantitative research methods were used to test the hypotheses, using nationally representative samples of architecture and engineering students in their fourth year of college coursework. A total of 336 student responses were analyzed for the architecture sample, and 1,853 responses were analyzed for the engineering sample. Descriptive statistics were used to characterize design thinkers, and parametric tests compared design thinking measures across sample groups.

4.1 Data Collection

The target group for both samples were students in their final year of study at four year institutions with accredited engineering and architecture programs. Engineering students were surveyed with a paper-and-pencil instrument as part of a larger study, and architecture students were surveyed with an online instrument that only contained the design thinking and empathy scales. A total of 2,095 responses were collected from engineering students and a total of 395 responses were collected from architecture students. The number of responses analyzed from each sample was 1,853 and 336, respectively (Table 11). The sample size decreased from collection to analysis because some students did not answer an adequate number of questions on the design thinking scale (at least five) and some did not meet the target group requirements based on filter questions that were incorporated into the survey. However, both samples are representative of the national populations of engineering and architecture students in their final year of study.

Table 11. Sample sizes and distribution statistics

Design Discipline	Data Collected	Data Analyzed	Distribution Statistics of Design Thinking Responses		
	(n)	(n)	skewness	kurtosis	s
Engineers	2,095	1,853	-0.38	1.69	0.456
Architects	395	336	-1.34	4.14	0.467

4.1.1 Engineering Sample Collection

The sampling frame for engineering students included four-year engineering institutions available through the National Center for Education Statistics. A stratified random list of institutions was compiled by separating small (<5,400), medium (5,400-14,800), and large institutions (>14,800) by overall undergraduate enrollment. Engineering department heads were the initial point of contact for each institution. After making contact with the department head, capstone design instructors were asked to distribute the survey to their students. A total of 83 capstone design courses agreed to participate. No incentives were provided, but instructors were offered access to the raw, non-identifiable data in return for their assistance. Capstone design instructors were mailed paper surveys and were provided with instructions to distribute the surveys in their senior engineering courses. 66 instructors returned survey responses. A national sample of n=2,095 engineering students was collected. Respondents had the option to provide a home ZIP code through the survey. The home ZIP codes are depicted in Figure 5. Dots indicate home ZIP codes for at least one respondent. The engineering sample is nearly six times the size of the architecture sample because there are several sub-disciplines within engineering. For example, the sample of engineering students collected here is representative of eight engineering sub-disciplines: biomedical (n=55), civil (n=356), chemical (n=436), electrical/computer (n=288), environmental (n=44), industrial (n=165), mechanical (n=469), and materials science (n=36).

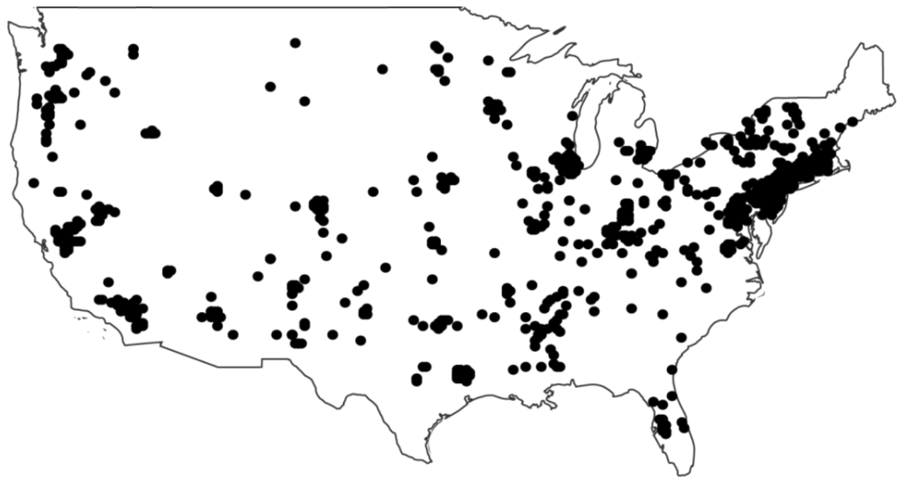

Figure 5. Engineering student respondents by home ZIP code

4.1.2 Architecture Sample Collection

Similar to the engineering sample, the sampling frame for architecture students included four-year institutions available through the National Center for Education Statistics. However, unlike a Bachelor of Science in Engineering, the Bachelor of Architecture is a professional degree that requires five years of study. Both professional and pre-professional architecture programs were contacted for participation; therefore; the sample includes responses from both fourth year and fifth year architecture students. The number of architecture departments within the U.S. is much less than the number of engineering departments (due to the number of engineering sub-disciplines). Therefore, every undergraduate architecture program in the nation, 129, (from the list acquired through the National Center for Education Statistics) was contacted to request participation in the survey. Architecture department heads were the initial point of contact. After making contact with the department head, instructors of studio courses were asked to distribute the survey to students in their final year of architecture studies via an email link. Out of 129 programs, 35 programs agreed to distribute the survey link to their students. Since the response rate from online surveys is typically lower than paper-and-pencil surveys, incentives of five dollar amazon gift cards were distributed to each respondent. Home zip codes were not requested from architecture students, and, to maintain confidentiality, the locations of the programs that participated are not disclosable. However, the location of the 35 program that participated indicate the sample is nationally representative.

4.2 Analysis Technique

Design thinking scores were calculated by averaging the existing data for each student. Design thinking scores range from 0 to 4 because the scale for each of the nine items ranged from "0-strongly disagree" to "4-strongly agree." A multi-factor analysis of variance (ANOVA) was conducted to compare design thinking scores between the sample groups. An ANOVA test determines significant difference between two or more groups based on comparison of the means.

A multi-factor ANOVA is utilized when it is believed that there is more than one factor, or independent variable, that could affect the dependent variable response (Ott & Longnecker, 2001). In the case of this study, the dependent variable was design thinking score and the independent variable of interest was design discipline (i.e. architecture or engineering). However, in Blizzard et al.'s (2015) prior study with freshmen engineering students, gender and academic achievement had a significant effect on design thinking score. Females made up a higher percentage of design thinkers than males, and design thinkers were higher academic achievers (Blizzard, et al., 2015).

The demographics of the samples collected for this study varied among these variables. The architecture student sample was 55% female and the engineering student sample was only 23% female- a trend consistent with enrollment in these majors. The architecture student sample also had a significantly higher percentage of students with an in-major average grade of "A" (57%) compared to the engineering student sample (39%). To account for potential effects of gender and academic achievement on design thinking and to prevent biased results, these variables were incorporated into the multi-factor ANOVA model in addition to the independent variable of design discipline.

5 Results and discussion

The multi-factor ANOVA model detected a significant difference ($p<0.0001$) in design thinking score based on design discipline. The average design thinking score of architecture students (3.30) was significantly higher than the average design thinking score of engineering students (2.59). The distribution of design thinking scores across each group is shown in Figure 6. The histograms communicate variation in scores between groups and the box plots provide a visualization of the median value for each data set.

Cohen's d effect size was calculated to quantitatively evaluate the amount of variation, or overlap, in design thinking scores between groups. The effect size is equal to the difference between the two samples' means divided by the standard deviation where an effect size larger than 0.8 is considered large (Cohen, 1988). In other words, calculating effect size answers the question: how big of a difference is their between the architecture mean score of 3.3 and the engineering mean score of 2.59? Effect size was calculated to be 1.4, which is a large effect size, meaning there is very little overlap between the scores of architecture and engineering students. Based on this result, the average architecture student would score higher than about 92% of engineering students on the design thinking scale.

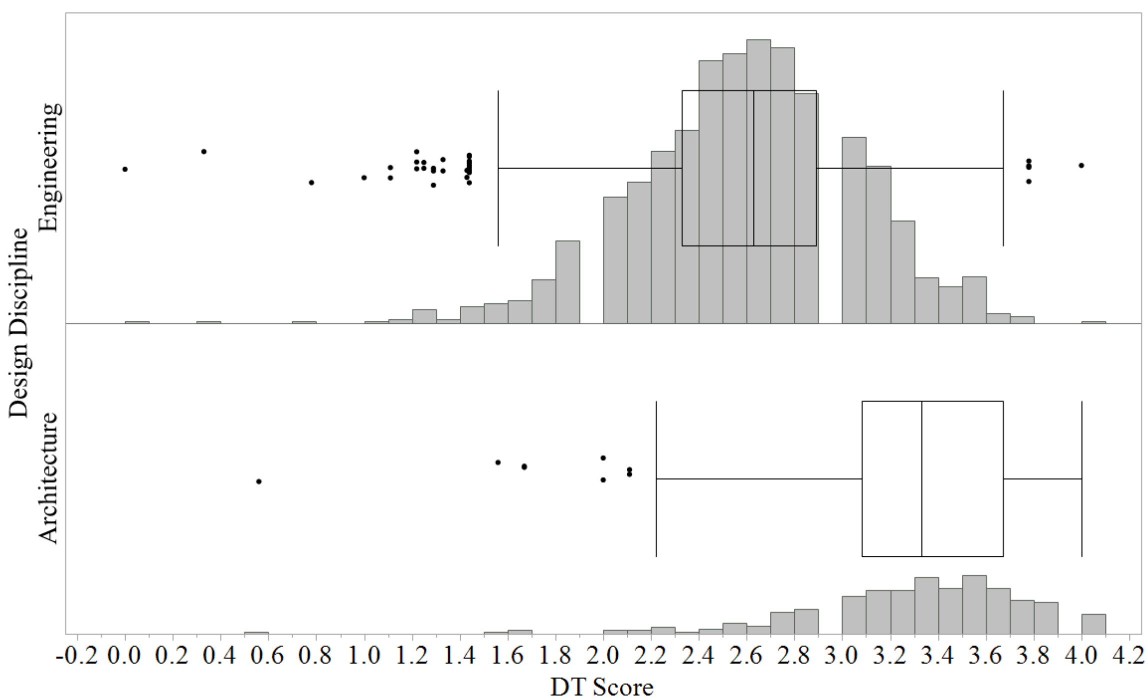

Figure 6. Distribution of design thinking scores for architecture and engineering students

To further distinguish design thinking ability between the groups, the architecture and engineering samples were separated into two groups of "design thinkers" and "non-design thinkers." Design thinkers were classified as students who scored in the upper quartile or 75th percentile (scored higher than 3.00) and non-design thinkers were classified as students who scored in the lower quartile or 25th percentile (scored lower than 2.38). Quartile cut-offs were calculated after lumping the architecture and engineering design thinking scores into one group. Figure 7 displays the percentages from each sample group that were design thinkers and non-design thinkers. Of the engineering students who took the survey, 14% were design thinkers and 28% were non-design thinkers. This can be compared to architecture students, where 75% were design thinkers and 4% were non-design thinkers.

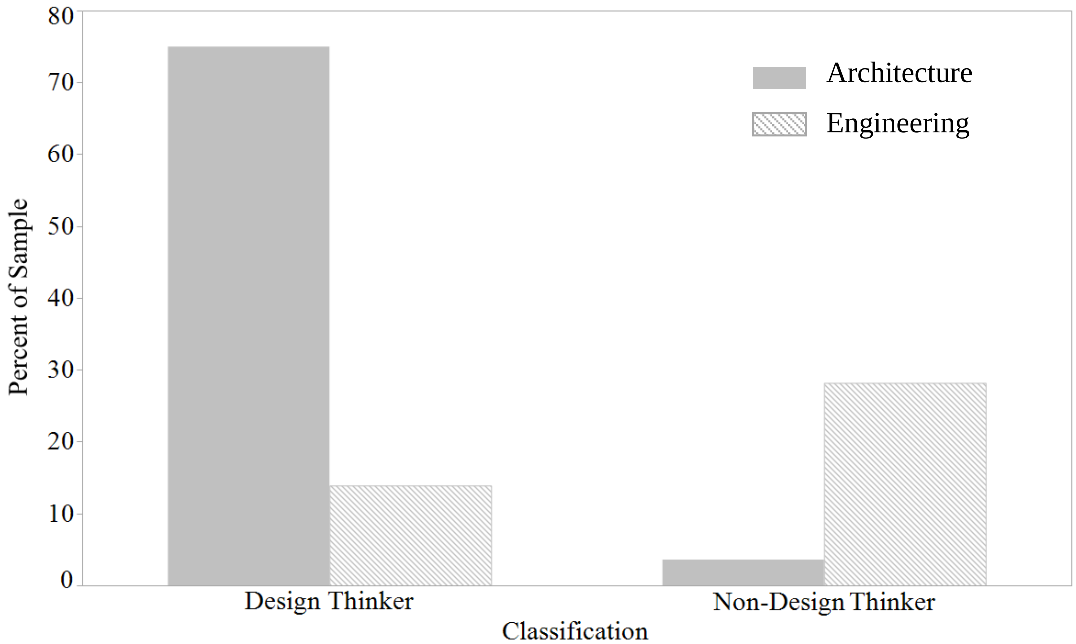

Figure 7. Percentage of samples who were design thinkers and non-design thinkers

When incorporating gender into the model, no significant effect was observed on design thinking scores ($p=0.057$) compared to the significance of the effect due to design discipline ($p<0.001$). This phenomenon is visualized in Figure 8 which illustrates that the groups' scores are significantly different due to design discipline and not gender.

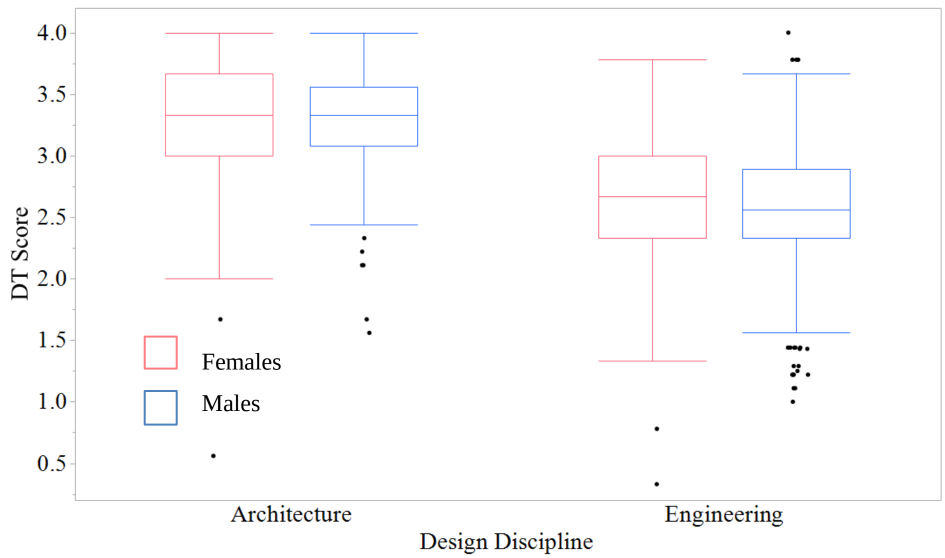

Figure 8. Effect of gender and design discipline on design thinking scores

When incorporating academic achievement into the model, the results are less clear. The difference in design thinking scores between groups is still significant, but the cause of this difference is not straightforward because of the interaction effect between design discipline and students who have an average academic grade of "A" ($p<0.0177$). This means distinguishing if differences in design thinking score are due to design discipline or high academic achievement is challenging. The data was examined more carefully to detect the most likely source of the difference. A box plot with design thinking score versus design discipline is overlaid with average in-major academic grade in Figure 9.

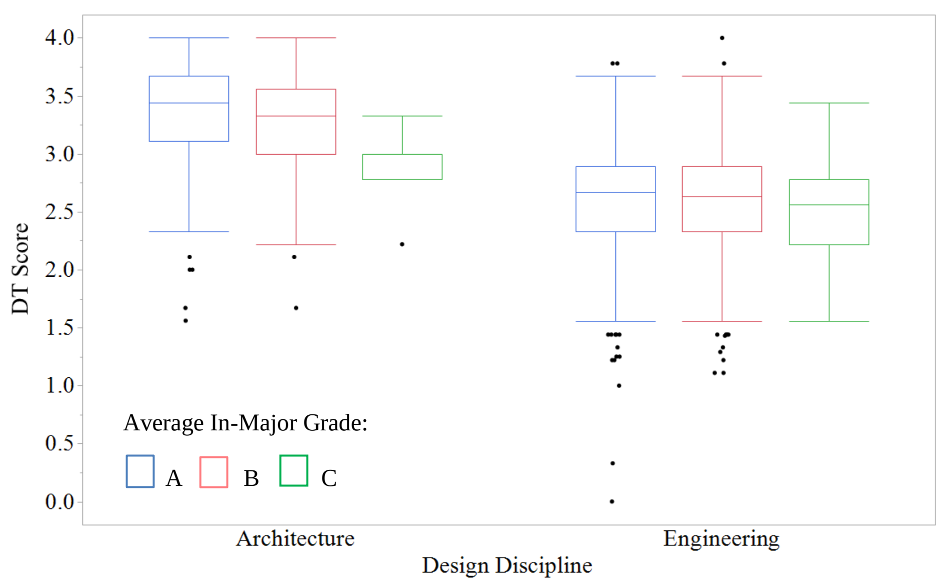

Figure 9. Effect of academic achievement and design discipline on design thinking score

A variation in design thinking score by academic grade does exist within the architecture sample, while variation in design thinking score by academic grade is minimal within the engineering sample. Despite the variation within the architecture sample, the median design thinking score of architecture students is consistently higher than the median design thinking score of engineering students across all levels of academic achievement. The higher median design thinking score of architecture students with an average in-major grade of "A" likely affected the average design thinking score of architecture students. However, the trend of higher design thinking score among architecture students holds true across all levels of academic achievement which indicates that design discipline plays an important role in the difference between design thinking scores.

6 Conclusions

This study provides compelling evidence of the separation in design thinking ability between architecture and engineering students at the conclusion of their undergraduate studies. 75% of the architecture sample was classified as design thinkers compared to only 14% of the engineering sample, and, on average, architecture students are significantly better design thinkers than engineering students, when defined by Brown's design thinking traits (Brown, 2008). The lack of value attributed to creative skill development within engineering education is likely a cause of this separation (Cropley, 2015). Additionally, studio design courses within the architecture curriculum set up architecture students to be better design thinkers because of their emphasis on prototyping, frequent student-teacher critiques on works-in-progress, and encouragement of divergent thinking- a key component of creative thinking (Kuhn, 1999). Prior research published within *Design Studies* has evaluated prototyping (Youmans, 2011), examined the benefits of critiques (Oh , Ishizaki, Gross, & Do, 2013), assessed creativity within architecture design education (Demirkan & Afacan, 2012), compared the design process between engineering students (Atman, Chimka, Bursic, & Nachtmann, 1999), and defined design thinking on a larger scale (Dorst, 2011); but the research presented in this article makes a unique contribution by conducting a big picture, quantitative comparison of design thinking across design disciplines.

The stark contrast between design thinking ability of architecture and engineering students holds important implications for engineering education. The National Academy of Engineers recognizes the need to develop engineers who are design thinkers (Dym, Agogino, Eris, Frey, & Leifer, 2005). Yet, implementation of studio courses that can help students develop these skills are scarce and ill-defined within the engineering education curriculum. In order to improve design thinking skills among their students, engineering educators should strive to implement pedagogical strategies commonly utilized within the architecture curriculum into engineering design courses. Within the past few years, engineering educators have been researching how to better teach creative skills and how to incorporate studio-based learning into the curriculum.

The engineering department at Harvey Mudd College was a trailblazer for creative skill development when they explored benefits of incorporating studio methods into introductory engineering courses (Little & Cardenas, 2001). Their studies along with other more recent studies can serve as excellent resources for engineering educators to incorporate design thinking into their curriculums. For example, Daly et al. (2014) show how assessments can motivate engineering students to improve their creative skills, and Connor et al. (2015) discuss the effectiveness of adopting studio based learning into engineering design. The incorporation of prototyping into the design process has also been shown to encourage divergent thinking of design students (Youmans, 2011). These are just a few techniques engineering educators can incorporate into their curriculum to improve engineering students' as design thinkers.

These results provide a starting point for exploration of design thinking separation between the architecture and engineering fields. A limitation of this study is that a greater percentage of design thinkers may have self-selected into the architecture field. However, another study recently found that senior engineering students scored significantly lower than freshmen engineering students on the design thinking scale (Coleman et al. 2018). This provides evidence to suggest that engineering education could be related to a decrease in design thinking ability and that a greater percentage of design thinkers within the architecture field is not simply a product of self-selection. Future studies could make longitudinal comparisons to determine if the separation in design thinking holds true for professional engineers and architects who have been working in the design industry. Due to the nature of the survey methodology utilized for this study, architecture and engineering students self-identified as design thinkers. Future studies could also build upon the results here by conducting experiments to empirically evaluate design thinking ability between the disciplines. This would provide evidence to suggest if self-identification matches actual ability.

7 References

Atman, C., Chimka, J., Bursic, K., & Nachtmann, H. (1999). A Comparison of Freshman and Senior Engineering Design Processes. *Design Studios*, 131-152.

Bairaktarova, D. (2017). The New Renaissance Artificers: Harnessing the Power of Creativity in Engineering Classroom. In *Creative Ways of Knowing in Engineering* (pp. 1-22). Springer International.

Bashier, F. (2014). Reflections on architectural design education: The return of rationalism in the studio. *Frontiers of Architectural Research*, 424-430.

Bennetts, C., Caldwell, B., Cheeley, A., & Green, M. (2017). Comparing Facets of Divergent Thinking in Engineering Freshmen and Upperclassmen. *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.* Cleveland: ASME.

Blizzard, J. (2013). *Design Thinkers Can Save the World: How Understanding their Interests, Goals, and Motivations can Inform Engineering Educators.*

Blizzard, J., Klotz, L., Potvin, G., Hazari, Z., Cribbs, J., & Godwin, A. (2015). Using Survey Questions to Identify and Learn more About Those who Exhibit Design Thinking Traits. *Design Studies*, 92-110.

Brown, T. (2008). Design Thinking. *Harvard Business Review*.

Buchanan, R. (1992). Wicked Problems in Design Thinking . *Design Issues*, 5-21.

Byrne, B. M. (1994). *Structural Equation Modeling with EQS and EQS/Windows: Basic Concepts, Applications, and Programming.* SAGE Publications Inc.

Cohen, J. (1988). The Concepts of Power Analysis. In *Statistical Power Analysis for the Behavioral Sciences* (pp. 1-17). New York, NY: Lawrence Erlbaum Associates.

Coleman, E., Shealy, T., Grohs, J., Godwin, A. (In Review). Design Thinking Declines during Undergraduate Engineering Education: A Cross-Sectional, National Study. *Journal of Engineering Education.*

Connor, A., Karmokar, S., & Whittington, C. (2015). From STEM to STEAM: Strategies for Enhancing Engineering & Technology Education. *International Journal of Engineering Pedagogy*, 37-47.

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. *Design Studies*, 54-91.

Cropley, D. H. (2015). Embedding Creativity in Engineering Education. In *Creativity in Engineering* (pp. 257-289). Elsevier Inc.

Daly, S., Mosyjowski, E., & Seifert, C. (2014). Teaching Creativity in Engineering Courses. *Journal of Engineering Education*, 417-442.

Darabi, H., Douzali, E., Karim, F. S., Harford, S., & Johnson, H. (2017). Life After University for Engineering Graduates. *ASEE Annual Conference & Exposition.* ASEE.

Davis, M. (1980). A multidimensional approach to individual differences in empathy. *JSAS Catalog of Selected Documents in Psychology*.

Demirkan, H., & Afacan, Y. (2012). Assessing creativity in design education: Analysis of creativity factors in the first-year design studio. *Design Studies*, 262-278.

Dorst, K. (2011). The core of 'design thinking' and its application. *Design Studies*, 521-532.

Dym, C., Agogino, A., Eris, O., Frey, D., & Leifer, L. (2005, January). Engineering Design Thinking, Teaching, and Learning. *Journal of Engineering Education*, 103-120.

Ercan, F., Sale, D., & Kristian, N. (2016). Innovative Curriculum to Enhance the Learning Experience of Electrical and Mechanical Engineering Students. *International Journal of Engineering Pedagogy*, 37-44.

Foley, S., & Kazerounian, K. (2007). Barriers to Creativity in Engineering Education: A Study of Instructors and Students Perceptions. *ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 539-555). Las Vegas: ASME.

Godwin, A. (2016). The Development of a Measure of Engineering Identity. *Jazzed about Engineering Education.* New Orleans, LA: American Society for Engineering Education.

Howe, S. (2010). Where Are We Now? Statistics on Capstone Courses Nationwide. *Advances in Engineering Education*.

Koppen, E., & Meinel, C. (2015). Empathy via Design Thinking: Creation of Sense and Knowledge. *Design Thinking Research*, pp. 15-28.

Kuhn, S. (1999). Learning from the Architecture Studio: Implications for Project-Based Pedagogy. *Mudd Design Workshop II, Designing Design Education for the 21st Century*, (pp. 195-200).

Kumar, S., & Hsiao, J. (2007). Engineers Learn "Soft Skills the Hard Way": Planting a Seed of Leadership in Engineering Classes. *Leadership Manage. Eng*, 18-23.

Little, P., & Cardenas, M. (2001). Use of "Studio" Methods in the Introductory Engineering Design Curriculum. *Journal of Engineering Education*, 309-318.

McKilligan, S., Fila, N., Rover, D., & Mina, M. (2017). Design Thinking as a catalyst for changing teaching and learning practices in engineering. *Frontiers in Education Conference.* Indianapolis: IEEE.

Mohan, A., Merle, D., Jackson, C., Lannin, J., & Nair, S. (2009). Professional Skills in the Engineering Curriculum. *IEEE Transactions on Education* (pp. 562-571). IEEE.

Nix, A. A., Lemke, M. T., Arlitt, R. M., & Stone, R. B. (2016). Design Education Across Disciplines: Opportunties for Curriculum Advancement. *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.* Charlotte.

Oh , Y., Ishizaki, S., Gross, M., & Do, E. Y.-L. (2013). A theoretical framework of design critiquing in architecture studios. *Design Studies*, 302-325.

Ott, R., & Longnecker, M. (2001). *An Introduction to Statistical Methods and Data Analysis.* Pacific Grove: Thomson Learning Inc.

Shealy, T., Valdes-Vasquez, R., Klotz, L., Potvin, G., Godwin, A., Cribbs, J., & Hazari, Z. (2016). Career Outcome Expectations Related to Sustainability among Students Intending to Major in Civil Engineering. *Journal of Professional Issues, 142*.

Sola, E., Hoekstra, R., Fiore, S., & McCauley, P. (2017, July). An Investigation of the State of Creativity and Critical Thinking in Engineering Undergraduates. *Creative Education,* 1495-1522.

Treffinger, D., Young, G., Shelby, E., & Shepardson, C. (2002). *Assessing creativity: A guide for educators.* Sarasota: The National Research Center on the Gifted and Talented.

Youmans, R. (2011). The effects of physical prototyping and group work on the reduction of design fixation. *Design Studies*, 115-138.

CONCLUSION

The manuscripts within this thesis suggest that there is work to be done within engineering education to improve the design thinking ability of engineering students. Chapter 1 shows that although freshmen engineering students enter college with higher design thinking ability than their counterparts, senior engineering students graduate with significantly lower design thinking ability than freshmen engineering students. Further, senior students across all sub-disciplines of engineering display lower design thinking ability than freshmen engineering students. Within Chapter 1, recommendations for engineering educators are provided that could help improve engineering design pedagogy. Recommendations that could contribute to design thinking ability include encouragement of divergent thinking and concentration on user-centered design within the engineering classroom.

Chapter 2 shows that senior engineering students also perform worse on the design thinking scale than senior architecture students. Engineering students were compared to architecture students in Chapter 2 because design thinking is central to architecture design education, opposite of engineering education where design thinking is rarely required. Recommendations within Chapter 2 suggest pedagogical techniques utilized with architecture education that could be translated to engineering education, especially adopting studio based learning into engineering design.

Next steps for this research are two-fold. In order to improve the quantitative methods utilized for the manuscripts in this thesis, future studies could make revisions to the design thinking scale. Revisions could include increasing the number of items utilized to measure design thinking as well as revising the items to better evaluate the five traits of design thinking. Additionally, qualitative studies could be conducted to bolster the quantitative results presented in this thesis. For example, experiments where the design abilities of engineering and/or architecture students are empirically observed based on completion of a design task rather than self-identified by a survey instrument. Despite the future studies that could be conducted, the results gathered through this thesis provide a quantitative perspective on the design thinking ability of engineering students that has not been largely explored in prior literature.