Comparing Design Thinking Traits between National Samples of Civil Engineering and Architecture Students

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Abstract

Civil engineers and architects are both trained in design thinking, but they approach the process of design from differing perspectives largely due to the divergence in their educational curriculums. With an interest in the effect of differing educational perspectives on design thinking outcomes, comparisons were made between the self-identified design thinking abilities of students in their final year of undergraduate civil engineering or architecture programs. Perceived design thinking ability was evaluated through a survey that was distributed to students enrolled in four-year institutions across the United States. The Analysis of Variance (ANOVA) test was used to compare

responses between the civil engineering (n = 356) and architecture (n = 335) student samples. There is a significant difference in perceived design thinking ability between the groups. Architecture students score higher than civil engineering students on all design thinking traits. Based on these results, the civil engineering curriculum may benefit from the incorporation of pedagogy that emphasizes design thinking, like studio-based learning.

Introduction

Civil engineers and architects both design for "complex living, working, playing, and learning systems or environments" (Buchanan, 1992, p.10). When designing for these environments, both disciplines consider "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 civil engineers and architects share similar design aims (Chan *et al.*, 2002), the curriculum standards they experience are vastly different (Wilkinson and Scofield, 2002). Engineering educators struggle to encourage creativity (Daly *et al.*, 2014) while architecture educators struggle to teach a balance between creativity and rationality in the design studio (Bashier, 2014).

Design thinking transcends the education within civil engineering and architecture because it requires a balance of rationality and creativity. Several definitions of design thinking exist and are explored in design research literature (Adams *et al.*, 2011; Dorst, 2011; Charnley *et al.*, 2011, Cross, 2006; Lawson, 2006; Visser, 2009). One commonly referenced definition of design thinking within industry is "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). This definition is widely accepted within management and service industries (Kleinsmann, *et al.*, 2017; Micheli, *et al.*, 2018). Included in Brown's definition are five non-exhaustive traits of design thinkers: (1) a willingness to ask questions and take new approaches to problem solving (experimentalism); (2) an ability to analyze holistically to develop novel solutions (integrative thinking); (3) an ability to adopt the psychological viewpoint of others in everyday life (empathy); (4) an ability to work with many disciplines (collaboration); and (5) refusal to back down from challenging problems (optimism) (Blizzard *et al.*, 2015; Brown, 2008).

The quantitative results presented in this paper compare the perceived ability of students from civil engineering and architecture related to Brown's five design thinking traits. Traits of design thinking remain a commonality between design disciplines, but differences emerge as a result of the domain. The domain independence of civil engineering and architecture creates a set of invariants about design thinking (Cross, 1982; Visser, 2009; Goel & Pirolli, 1992). The purpose of this paper is to measure the differences between civil engineering and architecture students with regards to their perceived design thinking ability.

Design education plays a critical role (Atman *et al.,* 2004; Adams *et al*., 2003) in civil engineers' and architects' skill development (Akin, 2001; Roozenburg & Cross, 1991). Comparing design competences, based on designers' field of expertise is a dynamic topic in design research. For example, researchers focused on quantitatively comparing industrial designers with architects (Goldschmidt & Rodgers, 2013), analyzing divergence in design fixation of industrial, mechanical and architecture students (Purcell & Gero, 1996), evaluating specifics in design thinking models and processes between architects and engineers (Akin, 2001; Roozenburg & Cross, 1991), and qualitatively assessing differences between designers of practice with designers of education (Gunther & Ehrlenspiel, 1999). The research presented in this paper uniquely contributes to the body of knowledge on design education research. Specifically, through a quantitative comparison of design thinking traits between national samples of civil engineering and architecture students.

The research presented in this paper builds on Blizzard *et al.*'s (2015) design thinking survey instrument. Blizzard and colleagues tested their design thinking questions on a national survey of U.S. students enrolled in their first year of college. Nine survey questions were validated and mapped to the five design thinking traits of *experimentalism*, *integrative thinking*, *feedback seeking*, *collaboration*, and *optimism* (Blizzard *et al.*, 2015). In their study, the researchers who developed the survey instrument (Blizzard *et al.*, 2015) acknowledge that qualitative traits of design thinking cannot be fully encompassed by nine quantitative survey questions. However, they advocate that this set of questions does allow for exploration and comparison of design thinking between sample groups like civil engineering and architecture students.

Blizzard et al.'s (2015) survey instrument was used in the study presented in this paper to evaluate perceived design thinking ability of civil engineering (n = 356) and architecture college students (n = 336) in their final year of college. The results presented in this paper explore differences between design thinkers in these two distinct disciplines. Despite differences in design thinking traits, these disciplines are often asked to collaborate on design tasks in the real world (Stein and Hess, 2003). Understanding how students from these two disciplines perceive their design thinking abilities may provide evidence to improve collaboration between these two groups (Coates, 1993) or explain why conflict may arise during the design process (Stein and Hess, 2003). The discussion offers some explanation in terms of discrepancies between educational curriculums, and the conclusion offers recommendations for civil engineering educators.

Background

Civil engineering design and architectural design models are rooted in two distinct approaches to design thinking. Civil engineering generally approaches design thinking by optimizing for a particular objective (Pahl *et al.*, 2007) while architecture often takes a more intuitive, holistic approach (Hillier, Musgrove, O'Sullivan, 1984). Civil engineering design models are mainly problem-focused where design problems are analyzed in sub-problems, and solutions are recomposed from partial ones in a procedural manner. A procedural approach to design thinking was explored in architectural design (Alexander, 1964) but presented shortcomings in its application (Alexander, 1965). Current architectural design thinking supports a less procedural, more iterative, and intuitive approach to design problem solving. Architectural design relies on the early formulation of pre-concept solutions or primary generators (Darke, 1979) as a means to structure the design problem.

Both models have limitations. In practice, architects and civil engineers build on both procedural, analytical strategies and intuitive, iterative ones (Roozenburg and Cross, 1991). Overall, designers' skills include abilities to resolve ill-defined problems, adopt solution-focused strategies, employ abductive reasoning (Cross, 2006) and use symbolic and analog representations of design knowledge and artifacts (Akin, 2001) to design and to communicate design artifacts (Zimring and Graig, 2001).

Design thinking traits

Differences between disciplines do exist, yet there are common traits among design thinking processes and skills defined in the literature. Commonalities are summarized into the design thinking traits listed in Table 1 (Blizzard *et al.*, 2015; Brown, 2008). Each design thinking trait relates to different facets of design thinking skills and processes. For instance, feedback seeking and empathy relate to the social situatedness of design (Schön, 1983), and the role of the designer as a part of a team in a social process (Dym *et al*., 2015). Integrative thinking implies that designers maintain sight of the big picture using strategies to decompose design problems and recompose design solutions (Akin, 2001) using systems thinking (Dym *et al*., 2015). Optimism and the search for a better solution relates to a creative and innovative solution-focused design thinking process (Cross, 2005). Experimentalism approaches design as an inquiry and an opportunistic iteration (Visser, 2009) between divergent and convergent thinking that entails a co-evolution of the design space (Maher & Poon, 1996; Dorst & Cross, 2001). Finally, collaboration is inherent to design thinking as the complexity of design artifacts rest on a diversity of knowledge contributed by different designers to the design process (Dym *et al.*, 2005). The multiplicity of design languages, symbolic and analog (Akin, 2001), supports communication between designers (Dym *et al.*, 2005).

Differences between civil engineers and architects' approach to design, in relation with design thinking traits

Akin (2001) points out differences in civil engineers and architects cognitive design thinking process. He states that differences are anchored within each disciplines' ethos and culture, and the differences are supported by each profession and educational philosophy. According to Akin (2001), civil engineers tend to use routine design strategies, fixate on a satisfying solution without searching for alternatives, use standardized schemata to decompose design problems, and rely on predetermined procedures (Akin, 2001). This routine, standardized approach to design within the civil engineering field is reinforced by the American Society of Civil Engineer's (ASCE) Body of Knowledge (BOK), which states "the design component at the undergraduate level should involve application of the design process under a defined set of standards and constraints." (ASCE, 2019, p. 36). Architects, on the other hand, work in a professional culture which incentivizes creative and inventive strategies which push on constraints and challenge standards. Architects search for alternative solutions even if one solution has been found, and they depend on non-standard and idiosyncratic strategies to decompose design problems and recompose design solutions.

Akin (2001) also points out differences in design artifacts. The architectural artifact is socially situated; it must fit into a social context and address its users' functional, economical, ergonomic, cognitive, and psychological needs on a continuous basis. Engineered artifacts often answer to a smaller set of user needs. The ASCE's BOK states that civil engineers must consider "risk assessment, standards, codes, regulations, safety, security, sustainability, resilience, constructability, and operability at various stages of the design process." (ASCE, 2019, p. 36). There is mention of considering societal impacts, but user-centered design is not emphasized.

The prominence of constraints on design artifacts differs between disciplines. This difference in focus on constraints affects designers' interaction and collaboration with end users. Engineered artifacts are often associated with "invisible" design processes, such that the end-user's lack of technical expertise may hinder collaboration with the designer (Zimring and Graig, 2001). This is sometimes contrary to architectural drawings, which are understandable by the end-user, thus favoring collaboration and integration of the end-user into the design process. The differences in design thinking approaches between civil engineers and architects are categorized in relation to the non-exhaustive design thinking traits pointed out by Blizzard *et al.* (2015) and Brown (2008) in Table 2. Domain-dependent divergence in design thinking suggests potential differences in design traits between civil engineers and architects.

Comparisons of design education across civil engineering and architecture

Educational philosophies are grounded in each design disciplines ethos, beliefs, models, and culture. Engineering education follows a science-based and problem focused philosophy (Akin,

2001) whereas architectural education tends to be arts-based (Roozenburg and Cross, 1991) and focused on the proposal of innovative, creative solutions. The literature discussed in this section provides an overview of major differences between civil engineering and architecture curriculums that could lead to differences in the types of design thinkers they produce. The curriculums of civil engineering and architecture programs are continuously evolving (Connor, Karmokar, & Whittington, 2015), but the present study draws comparisons situated within pedagogical philosophies of the majority rather than evolving philosophies of the minority, similar to Atman *et al.*'s (2004) broad characterization of design within engineering education.

Civil engineering and architecture design curriculums were compared within this literature review in terms of the five design thinking traits listed in Table 2. Civil engineering pedagogical commitment to these traits is less clear (Cropley, 2015; Howe, 2010; Zancul *et al*., 2017) than in architectural education (Bashier, 2004 ; Kuhn, 1999) because 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 and industrial design, not engineering (National Academy of Engineering, 2005; 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 curriculum; while five engineering programs stated that studio education was nonexistent in their curriculum (Nix *et al.*, 2016). Some 21st century approaches in engineering education, and more specifically civil engineering education, have experimented with studio pedagogy, but it is still relatively rare (Zancul *et al.*, 2017; National Academy of Engineering, 2005). The definition of studio pedagogy within engineering education ranges widely from an isolated environment where students teach themselves with guided computer exercises (Little & Cardenas, 2001; Connor, Karmokar, & Whittington, 2015; Ercan, Sale, & Kristian, 2016) 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.

Prototyping and design iterations

Architecture studio courses also emphasize prototyping or in Kuhn's words, "design[ing] solutions which undergo multiple and rapid iterations," (Kuhn, 1999). In contrast to the architecture curriculum where prototyping is central to the studio design experience, only 37% of engineering students indicate that prototyping was a topic taught in their engineering design courses (Howe, 2010). For those engineering courses that do incorporate prototyping, they often take a traditional engineering approach where just one prototype is produced rather than multiple iterations (Zancul *et al.*, 2017). The development of only one prototype is disadvantageous for the development of design thinking skills. An iterative prototyping technique is essential to design thinking because a focus within design thinking is taking a human-centered, iterative approach (van der Bijl-Brouwer & Dorst, 2017).

One objective of iterative prototyping is incorporation of user feedback for an improved final product that better meets users' needs. The feedback seeking involved in iterative prototyping acknowledges the importance of meeting the end-users' needs which is a significant component of empathy. Moreover, design iterations support parallel lines of thoughts (Lawson, 1993) that allow the exploration of design alternatives. Because iterative prototyping incorporates, experimentalism, feedback seeking, and requires empathizing with the user, architecture students may have a higher perceived design thinking ability than civil engineering students.

Critiques and teacher feedback

Civil engineering and architecture design courses differ in the frequency of both formal and informal critique on works-in-progress by peers and instructors. Sixty-six percent of engineering students in capstone design courses said finding time to work on their design project was either entirely or partially their responsibility, meaning 66% did not have a class period dedicated purely to project work (Howe, 2010). The limited time during class periods to work on projects in the current engineering capstone format, limits time for instructors to provide students with a critique on works-in-progress.

Civil engineering design courses generally involve presentations of progress, but they are infrequent and predominately formal (Labossière and Roy, 2015). Ninety-two percent of engineering students reported having 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 of capstone engineering students (55%) said their designs were never reviewed (Howe, 2010). Instructors' feedback, when provided, entice different design thinking behavior either promoting a convergent or divergent design process (Yilmaz and Daly, 2016). Without having their designs challenged through review or critique, civil engineering students are not frequently given the opportunity for divergent thinking through ideation, which is a crucial component of experimentalism. This shortcoming of civil engineering design education may be detrimental to civil engineering students' perceived design thinking ability. In addition, minimal time for project work during class does not encourage collaboration between peers nor instructor.

Creativity

A third key difference between civil engineering and architecture design education is comfort with the concept of creativity, specifically divergent thinking in pedagogical approaches. The challenge when incorporating creativity into any design curriculum whether civil engineering or architecture is maintaining a balance between divergent and convergent thinking, promoting an openness of thinking (Beiler, 2015) while also providing a certain amount of guidance (Bucciarelli, 2003).

Architecture courses, in particular, tend to emphasize divergent thinking or the "generation of ideas" (Treffinger *et al.*, 2002). They also promote thinking outside of the box with project assignments that are complex and open-ended (Kuhn, 1999). Creative responses are often encouraged within architecture studio courses to support designing innovative and artistic forms (Bashier, 2014). Generation of ideas or divergent inquiry allows for conceptual thinking where answers are not required to have "truth value", meaning answers are not always verifiable (Dym *et al.*, 2005). This way of thinking directly conflicts with principles at the core of engineering science that is taught in civil engineering curriculums (Akin, 2001). It would be unacceptable for a civil engineering student to respond to a final exam question in a civil engineering course by providing multiple concepts with no "truth value" (Dym *et al.*, 2005).

Convergent thinking is well represented in civil engineering design courses (McKilligan *et al.*, 2017), but instruction on generating ideas and openness to exploring ideas is less evident (Daly *et al*., 2014; Yilmaz & Daly, 2016). As an illustration, a recent study found that engineering students who view themselves as highly creative are less likely to graduate with an engineering degree (Atwood & Pretz, 2016), an indication that ideologies of incorporating creativity into civil engineering education are still at odds with practitioners views of civil engineering design (Bucciarelli, 2003). The literature review presented throughout this section contributes to exploring differences between civil engineering and architecture curriculums, in relation to their impacts on design thinking traits. This relationship is illustrated in Figure 1.

Fig. 1. Characteristics of design education that affect design thinking traits

Based on the information presented, it seems as though the architecture curriculum may better prepare students to become design thinkers than their engineering counterparts. However, civil engineering educators have recently begun to incorporate design thinking concepts into the civil engineering curriculum (McKilligan *et al.*, 2017; Zancul *et al.*, 2017; Connor *et al.*, 2015). Many of these courses and subsequent research studies about it are still experimental, and it is unclear whether these developments are being incorporated into the civil engineering curriculum on a larger scale. By surveying a national sample of civil engineering and architecture students, the research presented in this paper seeks to bring new insight to some of this uncertainty.

Questions and Hypotheses

The purpose of the research presented in this paper was to explore differences in perceived design thinking ability between civil engineering and architecture students. The research questions that guided this research include:

1) What differences exist in perceived design thinking ability between undergraduate civil engineering and architecture students in their final year of college?

2) Does one discipline hold higher perceptions than the other for certain design thinking traits?

Answering these questions fills a gap in the literature providing a national, quantitative comparison of perceived design thinking ability between architecture and civil engineering students. The hypotheses corresponding with the research questions are:

1) Architecture students have a higher perceived design thinking ability than civil engineering students during their final year of undergraduate studies.
2) Architecture students hold higher perceived abilities than civil engineering students in the experimentalism and collaborative design thinking traits, based on Kuhn's (1999) principles of architecture studio education.

Methods

Survey Development

The survey to measure design thinking traits between civil engineering and architecture students is based on Blizzard *et al.*'s (2015) study. Explanations of the instrument are provided in this section along with an explanation of methods used for their validation.

Design Thinking Scale

In 2012, Blizzard and colleagues administered a nationwide survey titled Sustainability and Gender in Engineering (SaGE) 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 1) mapped to five design thinking traits: collaboration, integrative thinking, experimentalism, optimism, and feedback seeking (Blizzard *et al.*, 2015). The design thinking instrument, as developed by Blizzard and colleagues, is shown in Table 3. Each item underwent a detailed exploratory factor analysis and were categorized into traits as a result of that process.

The design thinking instrument developed by Blizzard *et al.* (2015) includes four of the five design thinking traits from Brown (2008): integrative thinking, optimism, experimentalism, and collaboration (Table 1). To measure one aspect of the empathy trait, Blizzard *et al.* (2015) also included feedback seeking. The items “I seek input from those with a different perspective from me” and “I seek feedback and suggestions for personal improvement” described this feedback seeking variable which captured students’ willingness to seek input from others in design.

Validation of the Survey Instruments

When conducting research with a survey instrument, the survey questions must appropriately measure the intended variable for the target sample group. This section describes the techniques used to validate the survey instrument. Validation methods ensure that the survey instrument measures a single latent variable. The expectation is that the instrument is capable of measuring design thinking (Blizzard *et al.*, 2015). However, when the instrument was created, it was validated with samples that did not represent the responses of civil engineering or architecture students. The instrument was originally intended for first-year college students. The original validation of the instrument was conducted by previous researchers (Blizzard *et al.*, 2015). A summary of their exploratory factor analysis is provided below. The authors of the present study conducted a secondary, confirmatory analysis to validate the survey instruments with civil engineering and architecture student samples.

Exploratory Factor Analysis

Exploratory factor analysis (EFA) is a technique commonly used in the development of survey instruments. When researchers develop survey instruments, EFA is used to determine the number of latent variables that a survey instrument measures for some sample population. The latent variables are inferred by the researcher on the basis of a theoretical framework in conjunction with the statistical test. The design thinking instrument used for this study was developed based on a prior theoretical framework of design thinking (Blizzard *et al.*, 2015). The authors of Blizzard *et al.* (2015) performed an EFA on the design thinking instrument. They found that the instrument measured five factors when applied to a first-year college student sample. The five factors shown through their EFA were indicative of the five design thinking traits previously described, including feedback seeking, integrative thinking, collaboration, optimism, and experimentalism. These five factors are theorized to represent design thinking as the latent variable.

Confirmatory Factor Analysis

Confirmatory factor analysis (CFA) is a technique commonly used for the validation of survey instruments. A CFA is typically performed after an EFA to determine if the factor structure determined by the EFA persists when the survey instrument is applied to a different sample population. The authors conducted a CFA to ensure that the design thinking instrument developed by prior researchers with a first-year college student sample (Blizzard *et al.*, 2015) was appropriate for measurements of design thinking within the populations of interest, civil engineering and architecture students.

Two confirmatory factor analyses were conducted using the lavaan package in R (Rosseel, 2012). CFA was conducted on architecture (n=335) and engineering student (n=356) samples for the design thinking instrument from Blizzard *et al*. (2015). Several fit indices of the CFA were evaluated based on Byrne's suggestions (Byrne, 1994) 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). The *RMSEA* is a better indicator of fit than *CFI* or *TLI*, and is less sensitive to changes in sample size (Schumacker & Lomax, 2004), so it gives the most weight when evaluating the fit indices, listed in Table 4. The design thinking, five-factor model was a good fit for the architecture student sample (*RMSEA* = 0.05) and a moderate fit for the civil engineering student sample (*RMSEA* = 0.06).

Sampling and Statistical Analysis

Responses from civil engineering and architecture students in their final year of college were collected through a stratified random sampling (SRS) procedure. A total of 335 student responses were analyzed for the architecture sample, and 356 responses were analyzed for the civil engineering sample. Parametric statistical tests were used to compare design thinking measures between the groups.

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. The sampling frame for each group consisted of four-year institutions offering accredited civil engineering and architecture programs. Lists of these programs were obtained from the National Center for Education Statistics. Stratified random lists of institutions were compiled separately for architecture and engineering programs by separating small (<5,400), medium (5,400-14,800), and large institutions (>14,800) based on overall undergraduate enrollment. The authors contacted a random number of programs from each list. The gatekeepers for distribution of surveys were instructors of the students' senior design courses whom the researchers individually contacted via email. Students from fifteen civil engineering programs and thirty-five architecture programs participated in the survey. The programs that participated are distributed across the United States. The identities of individual programs are not published to protect the privacy of participants according to our IRB protocol. The random sampling procedure enables for the researchers to use statistical assumptions that infer the samples are representative of their larger populations.

Responses to the design thinking instrument were collected from eight engineering disciplines for a total of 2,095 responses from engineering students. Only civil engineering student data was considered for analysis in the present study, resulting in 356 civil engineering student responses. Architecture program data from thirty-five institutions resulted in 335 analyzable responses. Details on sample size and distribution are provided in Table 5. Distribution statistics of skewness, kurtosis, and standard deviation (Table 5) allow for the conclusion that the data is reasonably normally distributed, thus parametric statistical tests are appropriate for data analysis.

Analysis Technique

Perceived design thinking ability was measured by calculating a design thinking score for each participant. The score was calculated by taking the average of participant responses to the nine items of the design thinking instrument in Table 3. Scores were calculated for participants who answered at least five of the nine items. A five-level Likert scale was used for the nine items ranging from "0-strongly disagree" to "4-strongly agree," so design thinking scores also ranged from 0 to 4. Because this study was conducted through a survey, some bias is inherent due to self-identification. Self-identification means students may have overestimated their abilities when answering survey questions. This limitation is common with survey methodology that strives to evaluate the abilities of a group of interest. However, the risk of bias is decreased in this study because ability is compared between two groups within the same year of educational curriculum.

A three-way analysis of variance (ANOVA) was conducted to compare design thinking scores by discipline (civil engineering, architecture,), sex (male, female), and average in-major grade (A or B). Three-way ANOVA is a factorial ANOVA test and is utilized when testing the effect of two or more factors on the response variable (Ott & Longnecker, 2001). 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 as examined by skew and kurtosis (see Table 5). Sex and average in-major grade were considered in the analysis because Blizzard *et al.* (2015), found that first-year college students' sex and academic achievement had a significant effect on design thinking score. Because the participants were all in their final year of study, the number of participants with an average in-major grade of "C" was small (architecture: *n*=7, civil engineering: *n*=14). Given the small number of responses within this category, responses from participants with a "C" average were removed from the analysis to reduce the distribution's skew. Demographic breakdown of the samples by average in-major grade and sex are shown in Table 6.

Results

Differences in perceived design thinking ability between senior civil engineering and architecture students

The three-way ANOVA model showed that two interaction effects were significant: the interactions between 1) discipline and in-major average grade ($p = 0.022$) and 2) sex and in-major average grade ($p = 0.013$). In an orderly interaction, the order of the means for levels of factor B is the same even though the magnitude of the differences between levels of factor B may change from level to level of factor A (Ott & Longnecker, 2001). When the order of the means is the same, in an orderly interaction, the main effects of factors A and B can be considered independently. Least square means interaction plots from the ANOVA model were graphed to determine if the interactions were orderly or disorderly (Figure 2, Figure 3).

Fig. 2. Least Square Means Interaction Plots for Discipline and In-Major Average Grade

Fig. 3. Least Square Means Interaction Plots for In-Major Average Grade and Sex

The interaction between discipline and in-major average grade is orderly. However, the effect of grades on design thinking score are masked by discipline (Figure 2). This means the effect of discipline on design thinking score is meaningful, and the effects can be considered separately from in-major average grade; while the effect of in-major average grade on design thinking score should not be evaluated independently. The interaction between in-major average grade and sex is disorderly because the order of the means is inconsistent. Therefore, the effects of in-major average grade and sex should not be evaluated independently.

Discipline was the only treatment factor that had an independently, significant effect on design thinking score ($p < 0.0001$). The average design thinking score of architecture students ($M = 3.31$, $SD = 0.441$) was significantly higher than the average design thinking score of civil engineering students ($M = 2.59$, $SD = 0.456$). The distribution of design thinking scores across each sample is shown in Figure 4. In addition to the significant difference between the means ($p < 0.0001$), Figure 4 provides a visualization of minimal overlap between design thinking score distributions of civil engineering and architecture students.

Fig. 4. Distribution of design thinking scores for civil engineering and architecture students

Cohen's *d* effect size was calculated to quantitatively evaluate the amount of overlap in design thinking scores between the sample groups. Effect size is equal to the difference between the two samples' means divided by the standard deviation where 0.2 is a small effect size, 0.5 is a medium effect size, and 0.8 or higher is considered a large effect size (Cohen, 1988). Effect size was calculated to be 1.6 indicating a non-overlap of 73% between the design thinking score distributions of civil engineering and architecture students. An effect size of 1.6 is large and shows there is a significant difference in the distribution of scores between the groups, in addition to a significant difference between the means ($p < 0.0001$).

Effect of discipline for certain design thinking traits

The second question of interest was: does one discipline outperform the other for certain design thinking traits? Five three-way ANOVA models were calculated, one for each design thinking trait, to evaluate differences between the sample groups. A summary of significant results is given in Table 7.

Least square means plots were created for each significant interaction effect indicated in Table 7. Similar to results from analysis of overall design thinking score, interactions between sex and in-major average grade were disorderly, while interactions involving discipline were orderly. Therefore, the effect of discipline on each design thinking trait was independent of sex and in-major average grade. There was a significant difference between the means for all design thinking traits, with regards to discipline. Architecture students significantly outperformed civil engineering students on every trait. Descriptive statistics for the design thinking trait results are presented in Table 8 along with *p*-value and Cohen's *d* effect size.

Discussion

Civil engineers' and architects' design thinking approaches are rooted in two different models of design. Civil engineers approach design by optimizing for a particular objective (Pahl *et al.*, 2007), while architects tend to rely on a more intuitive and holistic approach (Hillier, Musgrove, O'Sullivan, 1984). In relation to Blizzard *et al.*'s (2015) design traits, these differing approaches to design thinking suggest that architects may score higher on perceived design thinking ability than civil engineers. Our results confirm this hypothesis. Our results also suggest that architecture education may promote design thinking more holistically than civil engineering education. Indeed, each disciplines' ethos and culture are supported by its educational philosophies (Akin, 2001).

Overall, and for each individual trait, architecture students' perceived design thinking ability significantly exceeds civil engineering students' perceived ability. Initial results revealed this significant difference, but to avoid bias, design thinking results were subsequently analyzed based on sex. It was necessary to analyze on the basis of sex because within the civil engineering sample, females outperformed males on the design thinking scale. However, when the effects of sex were combined with the effects of discipline, the effect of discipline ($p < 0.001$) dwarfed the effect of sex ($p = 0.06$) on perceived design thinking ability. Presenting results with sex incorporated, reinforces the strength of disciplinary effects on perceived design thinking abilities.

In addition to considering the effects of sex, design thinking results were analyzed considering the effects of academic achievement. Academic achievement, measured as in-major average grade, was of interest in the analysis because prior researchers found a correlation between academic achievement and design thinking score (Blizzard *et al.*, 2015). Our results show that academic achievement is positively correlated with the design thinking scores of architecture students, but not with those of civil engineering students. In other words, architecture students with higher in-major average grades had better design thinking scores. In-major average grade had no significant effect on the scores of civil engineering students. Incorporating academic achievement in our analysis provides a springboard for future research. Future researchers might investigate the following questions: are design thinking traits more useful for students' academic success within architecture than civil engineering, or have students who are more academically successful in architecture learned to develop these traits?

Among the design thinking traits analyzed, the significant disciplinary difference between feedback seeking scores must be noted ($p < 0.0001$, Cohen's $d = 2.5$). This significant difference may be a product of educational training. Notable differences in educational training include, but are not limited to, architecture pedagogical tendencies to promote iterative prototyping, encourage informal critiques, and advocate for creative thinking. Further discussion focuses on creative thinking as a source of feedback seeking tendency in architecture students.

Given civil engineering students' low average design thinking scores, in relation to architecture students ($M = 2.6$ vs. $M = 3.3$, $p < 0.0001$) the remaining discussion concentrates on hurdles to incorporate design thinking into civil engineering education. Shortcomings related to creative thinking development are addressed first, followed by shortcomings in divergent thinking development. We provide explanations on how these shortcomings may act as a barrier to the development of design thinking among civil engineering graduates. We conclude by offering recommendations to engineering educators.

Shortcomings of creative thinking development in engineering design education

Shortcomings of creative thinking in civil engineering education might be attributed to a lack of value placed on creative skill development (Cropley, 2015). Three barriers to teaching creativity in civil engineering education are: 1) overspecialization and narrow focus on technical content, 2) pseudo-expertise or teaching purely focused in factual knowledge rather than adaptive expertise, and 3) civil engineering faculty's focus on the "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). For example, a recent study found that creativity is not appropriately rewarded in engineering curriculum. Lack of reward for creativity leads engineering students who consider themselves to be creative to leave the engineering field in favor of more creative disciplines (Atwood & Pretz, 2016). In recent years, the National Academy of Engineers (NAE) has taken note of this shortcoming and recognizes the need to improve engineering design education.

NAE proposed an initiative calling for more creative engineering graduates by the year 2020 (National Academy of Engineering, 2004). Currently, engineering pedagogy decreases students' creativity from first-year to senior year (Sola *et al.*, 2017). However, improving creative ability is possible by taking small steps in creativity training (Sola *et al.*, 2017). Creative thinking influences design thinking, so shifting civil engineering pedagogy to develop creative skills may, in turn, improve the design thinking ability of civil engineering graduates (Bairaktarova, 2017).

Creative thinking relies on an iteration of divergent and convergent thinking (Goldschmidt, 2016). Both must be encouraged in design education. A recent study showed that engineering education failed to improve engineering students' capacity for divergent thinking (Bennetts *et al.*, 2017). The study compared divergent thinking between freshman and senior engineering students and found that both groups produced their most original ideas when conducting familiar tasks rather than unfamiliar tasks (Bennetts *et al.*, 2017). This finding is contrary to the definition of divergent thinking, "ignoring old assumptions to produce new ideas" (Bennetts *et al.*, 2017, p. 1), and demonstrates no significant difference in the ability to generate original ideas between first-year and senior engineering students.

Stagnation of divergent thinking development exhibited by Bennetts *et al.* (2017) aligns with another study published nearly twenty years prior. The study compared the design approach of first-year and senior engineering students (Atman *et al.*, 1999). First-year students 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" was observed more recently among engineering designers in professional practice (Crilly, 2015). The most recent version of ASCE's BOK states that, "the design process is open-ended and involves a number of possible correct solutions, including creative and innovative approaches" (ASCE, 2019, p. 36). More work must be done to incorporate this ideology into civil engineering education.

A decrease in creative ability (Sola *et al.*, 2017) and stagnation of divergent thinking over the course of an engineering education (Bennetts *et al.*, 2017) are reasons to believe engineering pedagogy is falling short of producing graduates with high perceived design thinking ability. A possible cause of these shortcomings is lack of faculty commitment to design pedagogy that incorporates creativity training and divergent thinking assessment (McKilligan *et al.*, 2017; Sola *et al.*, 2017; Dym *et al.*, 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).

Recommendations for civil engineering educators to improve design thinking in civil engineering graduates

The contrast between perceived design thinking ability of civil engineering and architecture students holds important implications for civil engineering education. The National Academy of Engineers recognizes the need to develop engineers who are design thinkers (Dym *et al.*, 2005). In fact, ABET refers to design as an "iterative, creative, decision making process" (ABET, 2018) which is reminiscent of design thinking as defined by Blizzard *et al.* (2015). Yet, implementation of civil engineering courses that help students develop design thinking skills appear scarce and ill-defined in the literature, an estimate of the number of courses is not available. A civil engineering studio design course could suggest pedagogical strategies ranging from isolated work in a computer lab to collaborating with an instructor one-on-one (Little & Cardenas, 2001).

In contrast, architecture studio design courses consistently train students to be design thinkers. Architectural design courses place emphasis on prototyping, design iteration, frequent student-tutor critiques, feedback on works-in-progress, divergent thinking, creativity, and ideation. Civil engineering educators can leverage opportunities to implement similar pedagogical strategies into civil engineering design courses for improving engineering students' design thinking skills.

Civil engineering explorations of studio-based learning are increasing as educators study how to teach creative skills and how to incorporate studio-based learning into the curriculum (McKilligan *et al*., 2017). For example, 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 civil engineering educators to incorporate design thinking into their curricula. Daly *et al.* (2014) showed how assessments can motivate engineering students to improve their creative skills, and Connor *et al.* (2015) discussed the effectiveness of adopting studio-based learning into engineering design courses. The incorporation of prototyping into the design process has also encouraged engineering students' divergent thinking (Youmans, 2011). Motivating students to improve their creative skills (Daly *et al.*, 2014) and incorporating greater opportunity for prototyping within design courses (Youmans, 2011) will help civil engineering educators satisfy ABET's expectation of design as an iterative, creative process (ABET, 2018).

Conclusions

This study provides evidence of a significant difference between the perceived design thinking ability of civil engineering and architecture students at the conclusion of their undergraduate studies. Architecture students excelled in their perceived design thinking ability based on five traits of design thinkers: feedback seeking, integrative thinking, optimism, experimentalism, and collaboration. Civil engineering students in our sample fell short in all design thinking traits when compared to the architecture students.

Quantitative comparisons of design thinking ability between nationally representative samples of civil engineering and architecture students use the scale developed by (Blizzard *et al.*, 2015) as it was intended, for making broad categorizations. The findings from this study also build on Blizzard *et al.*'s (2015) study by addressing three of their future research goals: 1) testing new questions, 2) conducting a confirmatory factor analysis, and 3) studying how design thinking traits are impacted by various factors. The confirmatory factor analysis conducted in the present study showed promising results because the design thinking scale was transferable to sample groups outside of the original sample.

A limitation of the present study is that a greater percentage of design thinkers may have self-selected into the architecture field. Future studies should explore why and how students choose to major in architecture versus civil engineering. Future research should also conduct longitudinal studies to determine if a causal link exists between education and design thinking. However, a recent study on engineering education found that senior engineering students scored significantly lower than first-year engineering students on the design thinking scale (Coleman *et al*., 2019). This might suggest that a higher perceived design thinking ability among senior architecture students is not simply a product of self-selection into the architecture field.

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Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1. Design thinking traits based on literature

Design thinking traits (Blizzard *et al*., 2015)	Design thinking traits (Brown, 2008)	Design skills and processes
Feedback seeking - they ask questions and look for input from others to make decisions and change directions.	**Empathy** - imagine the world from multiple perspectives	• Think as a part of a team in a social process (Dym *et al*., 2015) • Design is socially situated (Schön, 1983) and address aesthetic, ergonomic, psychologic, economic, and technical needs (Akin, 2001)
Integrative Thinking - they can analyze at a detailed and holistic level to develop novel solutions.	**Integrative thinking** - not only rely on analytical processes but also see aspects of a confounding problem and create novel solutions that go beyond and dramatically improve on existing alternatives	• Maintain sight of the big picture by including systems thinking and systems design (Dym *et al*., 2015) • Strategies to decompose design problems and recompose design solutions from partial ones (Akin, 2001)
Optimism - they do not back down from challenging problems	**Optimism** – propose better solution than existing alternatives even with high constraints	• Solution-focused strategies (Cross, 2005)
Experimentalism - they ask questions and take new approaches to problem solving	**Experientialism** - pose questions and explore constraints in creative ways that proceed in entirely new directions	• Tolerate ambiguity by viewing design as an inquiry or as an iterative loop of divergent-convergent thinking and handle uncertainty (Dym *et al.*, 2015) • Opportunistic iteration (Visser, 2009) • Co-evolution of problem solution / space (Maher & Poon, 1996; Dorst & Cross, 2001)
Collaboration - they work with many different disciplines and often have experiences in more than just one field.	**Collaboration** – enthusiastic interdisciplinary collaborator	• Think as a part of a team in a social process and communicating in several languages of design (Dym *et al*., 2015)

Table 2. Differences between architects and civil engineers' approach to design thinking in relation to design thinking traits

	Architects	Civil Engineers
Feedback seeking	• Socially situated – design to fit in a social context that addresses functional, ergonomic, psychological, cognitive needs (Akin, 2001)	• Either socially situated, respond to technical needs, or ergonomic needs or user cognitive needs (Akin, 2001)
Integrative thinking	• Complexity management strategies (recompose of comprehensive design solution from partial ones) (Akin, 2001) • Integrate analytical into the dominant intuitive approach to problem solving (Roozenburg and Cross, 1991)	• Predetermined procedures to handle interactions between parts of solutions (Akin, 2001) • Integrate intuitiveness into the dominant analytical approach to problem solving (Roozenburg and Cross, 1991)
Optimism	• Search for alternative solutions (Akin, 2001)	• Design fixation on satisfying solution (Akin, 2001)
Experientialism	• Dominance of creative inventive strategies (Akin, 2001) • Non-standard problem individual composition strategies (Akin, 2001)	• Dominance of routine design strategies (Akin, 2001) • Standardize schemata to decompose problems (Akin, 2001)
Collaboration	• Easy collaboration with end users through design representations (Zimring & Graig, 2001)	• Complex collaboration with end users (Zimring and Graig (2001) cited in Visser (2009)

Table 3. Design thinking instrument (Blizzard, *et al*., 2015)

Design thinking traits	Survey questions
Feedback seeking- 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 do not 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.
Collaboration- they work with many different disciplines and often have experiences in more than just one field.	• I hope to gain general knowledge across multiple fields. • I often learn from my classmates.

Table 4. Confirmatory factor analysis fit indices

	Design Thinking Scale		
	CFI	**TLI**	**RMSEA**
Architecture (*n*=335)	0.974	0.948	0.05
Civil Engineering (*n*=356)	0.970	0.941	0.06

Table 5. Sample sizes and distribution statistics

Design Discipline	Data Collected	Distribution Statistics of Design Thinking Responses		
	n	skewness	kurtosis	*SD*
Civil Engineers	356	-0.28	0.03	0.456
Architects	335	-0.92	1.40	0.441

Table 6. Demographics by Percent of Sample Size

Design Discipline	Average In- Major Grade (%)			Sex (%)		
	A	B	C	M	F	N/A*
Civil Engineering	29.8	46.9	3.9	73.0	21.3	5.6
Architecture	50.7	35.8	2.1	39.1	46.9	14.0

*N/A = participant chose not to answer

Table 7. Summary of Significant Model Effects for Each Design Thinking Trait

Treatment Factor	**Optimism**	**Feedback Seeking**	**Collaboration**	**Integrative Thinking**	**Experimentalism**
A	***	****	****	****	****
B					
A x B				**	
C					
A x C	*		*		
B x C	**		*	**	
A x B x C		*	*	***	*

Treatment Factor Key: Factor A= Discipline, Factor B= Sex, Factor C= In-Major Average Grade

Significant Results Key: * $p<0.05$, ** $p<0.01$, *** $p<0.001$, **** $p<0.0001$

Table 8. Trait comparisons between architecture and engineering students

Design Thinking Traits	**Architecture (*M*)**	**Engineering (*M*)**	***p*-value**	**Cohen's *d***
Design Thinking	3.31	2.59	<0.0001	1.6
Feedback Seeking	3.46	1.66	<0.0001	2.5
Integrative Thinking	3.34	2.89	<0.0001	0.7
Optimism	3.21	2.93	0.0003	0.4
Experimentalism	3.15	2.66	<0.0001	0.6
Collaboration	3.33	2.91	<0.0001	0.6