FIRST-YEAR ENGINEERING STUDENT DESIGN: AN EXPLORATORY STUDY OF SPATIAL AND CREATIVE SKILL

by

JACLYN KUSPIEL MURRAY

(Under the Direction of Barbara A. Crawford)

ABSTRACT

This dissertation consists of a set of three studies examining two skills important to the engineering community of engineering practice (ECoP): spatial and creative skills. The overall purpose was to understand what repertoires of practice undergraduate students utilize as newcomers to the ECoP through the design of a package. The first study examined how assessments of object manipulation skills compared with one another and across gender. The study focused on, *How does gender and spatial skill compare across object manipulation assessments?*, which included evaluating correlations between mental rotations and spatial visualization assessment scores. Participants completed the Revised Purdue Spatial Visualization Test: Rotations (Revised PSVT: R). Results indicated significantly higher scores for males than females. In addition, mental rotations and spatial visualization results were significantly correlated with one another between and across assessments for male, but not female participants. The second qualitative study explored what introductory prospective engineers know and think about creativity in engineering to understand their implicit theories of design creativity. The study investigated, *In what ways do inbound and peripheral legitimate* *participants in the field of engineering, conceptualize creativity within product design and the design process?* Findings revealed varying conceptions of creativity in product design and the design process. The third study integrated spatial and creative skill scores to investigate possible patterns among males and females, and focused on, *In what ways does first-year engineering students' spatial skill level relate to creativity in design?* Findings suggested participants with high creative product rank scores utilized AutoCAD™, generated many ideas, did not modify designs, and were more likely to consider only one design. When spatial and creative data were merged, for comparison, three findings emerged. Although a small sample size, high creativity was synonymous with highly correlated spatial visualization scores. There were no significant differences in average creative scores between genders, but males did score at the highest levels while females did not. Overall the set of papers contributes to the limited inquiry into domain-specific spatial and creative skills associated with the field of engineering education. Overall findings have implications for pre-college teachers, college level engineering instructors, and policy makers.

INDEX WORDS: spatial skill, design, creative problem solving, engineering education

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DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2016

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For Matilda “Mary” May Tighe McDonald and Madelaine Tighe Meinhardt; two sisters from two generations ago who taught a little girl to be proud when she had nothing and humble when she had everything.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank Barbara A. Crawford, J. Steve Oliver, Jori N. Hall, and Craig Wiegert for their service as members on my doctoral committee. Dr. Oliver has consistently influenced my thinking about science teaching and learning. Dr. Hall, an expert in qualitative inquiry and mixed methods, is an extraordinary educator who provides educative experiences that foster transformative experiences in her students. Dr. Wiegert exudes passion for teaching and provides active learning opportunities in his physics courses to formatively assess student learning. Thanks you Dr. Wiegert for allowing me to join your physics majors course so I could observe you in action. And last but not least, thanks to Dr. Crawford for offering research opportunities, mentorship, and guidance throughout my doctoral experience.

I would also like to recognize those who helped with data collection: Hillary Tanner and Ben Thomas. In addition, thanks to James Ammons, Bo Idsardi, and Young Ae Kim who assisted with some data analysis.

Lastly, I would like to acknowledge my family for supporting my decision to go back to school to prepare for a career in education research.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The purpose of this dissertation is to understand how spatial and creative skill, and conceptions of engineering creativity, contribute to how first-year engineering students solve an ill-structured design problem.

Situated Learning

The subsequent collection of studies employs a situative perspective on learning. Situated learning adopts the stance that learning is contextual and dependent upon interactions with the physical and social world (Lave & Wenger, 1991; Greeno, 1998). Construction of meaning arises from contemplation of experience as singular occurrences or sequences of events. A synthesis of activity within a community (ie., family, school, or religious organization) discloses common practices central to the specific organization. Each community has a set of traditions and patterns of practice valued by its kinship. With experience the practices eventually become embedded in individuals' repertoires of practice—the sum total of all practices attained from participation in multiple communities (Rogoff et al., 2005), and affects how individuals think, know, and learn which ultimately shapes their being.

An affiliation with a particular community initiates the development of a practice-linked identity; an "identit[y] that people come to take on, construct, and embrace that [is] linked to participation in particular social and cultural practices" (Nasir & Hand, 2008,

p. 147). Furthermore, identity is situational and contingent upon specific activities and actors involved in certain social settings.

Individuals, at any given time, belong to multiple communities of practice (CoP). Lave and Wenger (1991) describe “[a] community of practice [as] a set of relations among persons, activities, and world, over time and in relation with other tangential and overlapping communities of practice” (p. 98). A CoP is a consortium of practitioners distinguished by common goals, actions, and resources to sustain a shared practice (Wenger, 1998). Every legitimate membership in a CoP offers an opportunity, through participation, to learn and experience the activities valued by the community.

Experience and learning mutually inform one another and have the capacity to enhance one another (Pugh, 2011). Transformative experiences—encounters that change individuals’ values or perspective, arise from creation of personal and/or conceptual meaning. These experiences, in particular, provide the foundation for future learning (Bransford & Schwartz, 1999). Learners exposed to educative experiences—those that have the potential to produce transformative experiences, are more likely to encounter a transformative experience (Dewey, 1938; Girod, Twyman, & Wojcikiewicz, 2010). Dewey (1938) suggested experience—learning by doing, was not enough to initiate a transformative experience. Dewey stated the experience must also be educative. By “educative” he meant one must participate in an assemblage of strategically placed experiences, positioned in time, for one to extend continuity of meaning across manifold facets of experiences.

The situative perspective, broadly defined, assumes interactions with the world through experience of membership in various subsystems contribute to each new unique experience. A CoP, organizational setting, family life, or school can serve as subsystems. The interconnecting subsystems affect one another as actors play distinct roles in different settings (Lave & Wenger, 1991; Greeno, 1998). For example, children may be mostly obedient to parents, but passive or assertive at school depending on the situation. Accumulated experience leads to the formation of an identity that is both discrete across subsystems and dynamic over time. When engaging with well-defined subsystems, individuals reveal an identity distinct from others they manifest during engagement in other subsystems. These identities are often disconnected, but influenced by experience and engagement with the world and its subsystems.

The situated perspective views all learning as contextually bound and is the product of engagement between the activity, environment, and agents (Lave & Wenger, 1991). Engaging in a CoP begins with peripheral participation. Newcomers seek to understand community practice (patterns of activity) through participation. Learning by observing, imitating, or modeling experts in a community of practice describes the cognitive apprenticeship approach whereby novices develop cognitive skills necessary for specific tasks within an authentic domain (Collins, Brown, & Newman, 1989).

Legitimate Peripheral Participation (LPP), in the context of situated learning, positions actors in a multi-dimensional space relative to the periphery and center of the CoP (Lave & Wenger, 1991). The journey, and subsequent path taken by actors, from the periphery (newcomers) to the center (expert) is nonlinear—a circuitous trajectory unique to each agent. Agents navigate through evolving perspectives as they come to know and understand diverse facets of the community.

Engaging in a CoP, or subsystem, can reveal disjointedness between subsystems, or individuals and their values. Incoherence of values or conceptions across subsystems can inhibit the learning process. Conceptual change techniques help reformulate ideas about inconsistent conceptions of particular communities of practice (Pintrich, Marx, & Boyle, 1993). Moreover, conceptual change is a necessary precursor for transfer of conceptions across contexts (Bransford & Schwartz, 1999).

In summary, the situative perspective goes beyond observing the cognitive and behavioral factors of individuals. It considers the interacting social milieu that impacts how individuals think and know. Regardless of past experiences and learning, all individuals have the capacity to learn and use experience in a proactive way to learn from future experiences and adapt to problems in new situations (Bransford & Schwartz, 1999).

Science, technology, engineering, and mathematics (STEM) comprise a variety of professional CoPs among the various disciplines STEM subsumes. Currently, (at the time this dissertation was written) the United States (US) has acknowledged STEM education as a priority. The urgency has prompted the National Science Foundation (NSF), by the congress, to fund grants such as Improving Undergraduate STEM Education (IUSE)—Professional Formation of Engineers and Revolutionizing Engineering Departments (RED). Specifically, these awards target immediate change in engineering departments and within engineering courses at post-secondary institutions.

Specific engineering communities of practice (ECoP) vary widely depending on disciplinary focus; however, there are some overarching themes. Spatial visualization and creativity are just two of the core skills identified as necessary for innovative design (NSF, 2010). CoEP emphasize the specific practices significant to specific engineering domains.

STEM, Spatial Skills, and Creativity

Spatial ability has emerged over the past half century as a recognized set of skills necessary for competency in STEM fields (Uttal & Cohen, 2012). Mathewson (1999) proposed that spatial skills help foster an understanding and development of diagrams, illustrations, maps, plots, and schematics. Each of these elements includes one or more metaphorical or analogical structures that convey meaning (Mathewson, 2005). The synthesis of information or ideas from multiple unrelated sources is a type of creativity. Mathewson (1999) describes successful science as creative science in the following passage:

> Successful science students should be able to demonstrate thematic understandings independently of the form of the curriculum. Students have "mastered" new material only when they can use the knowledge successfully in unfamiliar situations—to solve problems and be creative. Creative work relies on integrating and making use of multiple capacities and multiple sources of information (p.45).

In addition, Mathewson offers classroom strategies to enhance spatial skills such as providing students the opportunity to conceptualize scientific phenomenon, using active learning approaches, choosing visual analogies, and engaging in authentic tasks to focus on the practice of science as well as subject matter content.

Kell and Lubinski (2013) suggest creativity is linked to high spatial ability as evidenced by an analysis of a longitudinal study that investigated individuals who had high spatial ability as children and creative STEM achievements later in life. Researchers compared participants' patents and refereed articles with previous spatial ability scores. Those who acquired patents, but did not publish had below average verbal scores and high spatial scores. STEM publishers had similar spatial scores as patent holders in addition to higher than average verbal scores. Researchers concluded spatial ability "plays a unique role in developing new knowledge" and it should be investigated further (Kell et al., 2013, p. 1835).

The development of creative skills contributes to flexibility and an ability to handle change (Kind & Kind, 2007). Spatial insight problems merge spatial visualization and creative problem solving skills to provide students with an opportunity to practice solving ill-structured problems while sharpening spatial visualization skills. Insight problems, or creative problem solving, refers to non-routine problems that require new approaches unlike those used in standard algorithmic problem solving methods (Dow & Mayer, 2004). Insight problems often involve redefinition of the problem, also known as problem finding. Creative problem solving is an iterative process of divergent and convergent thinking that recursively requires generation and analysis of creative ideas. An openness to new unconventional ideas leads to transformation of impractical ideas into novel solutions.

Real world problems, guided by the creative problem solving process, could expand individual creative potential in preparation for future learning. Opportunities ought to be provided that integrate spatial reasoning in the form of data displays, process diagraming, modeling, etc., specific to subject matter content, with creative problem solving exercises. Familiarization with different STEM spatial representations during K-12 education provides experience with the practice of science, technology, engineering, and mathematics (NGSS, 2013). Exposure to these skills increases students' repertoires of practice as they start to form an engineering practice-linked identity.

Rationale

As stated above, the purpose of this dissertation is to understand how spatial and creative skill, and conceptions of engineering creativity, contribute to how first-year engineering students solve an ill-structured design problem. Chapter Two considers spatial (object manipulation) skills among students. Six assessments were administered to 433 students to gauge students' level of spatial skill and determine if assessments correlated with one another between and across gender. Chapter Three investigates students' conceptions of creativity in product design and within the design process. Lastly, Chapter Four explores the relationship between spatial skill and creative elements within product design and the design process. Correlations and trends in the data reveal differences among gender.

This dissertation aims to fill in a gap in the research literature, as minimal research has been conducted on the connection between STEM-related spatial and creative skill. This set of exploratory studies unites engineering-specific spatial knowledge with domain-specific creativity: functional creativity. The intention is to understand in what ways repertoires of practice emerge when first-year engineering students complete a domain-specific design task.

Individuals selectively choose from an accumulated repertoire of practices, a set of techniques, to employ during certain situations. Choices are made based on views that may or may not be consistent with the values of the CoP. Entry into a new CoP—one that prepares students to be engineers, is initially unstable. Individuals may experience an imbalance between personal conceptions of practice and tacit assumptions made visible through engagement with more central members to the practice. Removing instability affords individuals the opportunity to make informed choices about whether they want to engage as inbound or peripheral (Wenger, 1998) learners in the CoP.

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CHAPTER 2

SPATIAL ASSESSMENT COMPARISON AMONG PROSPECTIVE ENGINEERS: HOW DO TESTS OF SPATIAL SKILL MEASURE UP AGAINST ONE ANOTHER AND ACROSS GENDER?[1]

[1] Murray, J.K. To be submitted to *Cognition and Instruction.*

Abstract

Previous studies have indicated females do not score as high on spatial skill assessments as males. However, this investigation found females differed from males on only one spatial assessment. In particular, this study examined the spatial skill level of 433 first-year male and female students enrolled within a college of engineering at a large southeastern university. After gathering and analyzing data from a battery of object manipulation spatial assessments, the findings indicated males and females did not score significantly different from one another on five out of six assessments. A Mann-Whitney U test was conducted to determine whether there was a difference in the mean rank score of males and females on the Revised Purdue Spatial Visualization Tests: Visualization of Rotations (Revised PSVT: R) test. Results of that analysis indicated that there was a difference, $\chi^2 = 7.99$, $p < .01$ with males scoring higher than females, with an effect size of Cohen's $d = 0.53$. Males and females were also compared separately across all spatial assessments. A Spearman's rank correlation coefficient matrix was developed to visualize correlations between assessments and gender. Male participants showed significant (mostly) moderate correlations between all tests at the $p < .001$ level. Moreover, female participants suggested different strengths of correlation and significance across all assessments.

Introduction

Investigation into science, technology, engineering, and mathematics (STEM) professional knowledge has gained momentum since funding became available through government agencies and private sources. Spatial skill level is a known predictor of STEM achievement (Wai, Lubinski, & Benbow, 2009). Currently, K-12 instruction emphasizes both verbal and mathematical skills, but does not afford equitable attention to the spatial domain (Newcombe, Uttal, & Sauter, 2013; Kell & Lubinski, 2013). This investigation sought to understand the object manipulation skill level of first-year engineering students, and to characterize relationships among mental rotations and spatial visualization assessments.

Competence in spatial thinking arises from a broad set of interconnected cognitive skills that require knowledge of space, representation, and reasoning (NRC, 2006). Spatial skill can be assessed by domain-general or domain-specific means; the difference is context. Although the domain was engineering, the spatial assessment centered on context-free spatial skill. Specifically, aspects of reflection, dimensional transformations, and rotation were assessed. Object manipulation spatial skills are considered fundamental to the field of engineering and includes mental rotations and spatial visualization (Sorby, 2009). “Spatial visualization and [mental rotations] require the ability to mentally manipulate spatial forms from a fixed perspective” (Kozhevnikov & Hegarty, 2001, p. 746).

Assessments of mental rotation require individuals to mentally rotate images in space. These images or objects can be two-dimensional (2D) or three-dimensional (3D). Objects rotated in 2D have three degrees of freedom (two translational and one rotational) while those in 3D have six degrees of freedom (three translational and three rotational). Therefore, 3D mental rotation tasks should, in theory, be more difficult than 2D mental rotation tasks.

Spatial visualization entails rotation in addition to other manipulations that may change the shape of an object (French, Harman, & Dermen, 1976). This includes changing an object's size by folding, or the concatenation of multiple objects to create a new shape. Also the transformation of an object across dimensions (ie., 2D to 3D or 3D to 2D) constitutes spatial visualization. In essence, spatial visualization requires higher cognitive skill, compared to mental rotation, because it combines elements of manipulation with rotation.

Freshman, at the post-secondary level, often lack formal spatial instruction necessary to enhance spatial skills, knowledge, and thinking (Deno, 1995). Empirical evidence suggests STEM professionals eventually acquire high dynamic spatial thinking skills (NSF, 2010; NRC, 2006; Okamoto, Kotsopoulous, McGarvey, & Hallowell, 2015) during early childhood development (Wai et al., 2009). Individuals entering college with weak spatial skills are sometimes offered an opportunity to improve skills with a course specifically designed to support spatial development (Sorby & Baartmans, 2000). Studies at the K-12 and post-secondary level suggest components of spatial thinking (skills and knowledge) can be learned (NRC, 2006; Yurt & Sunbul, 2012; Cakmak, Isiksal, & Koc, 2014; Okamato et al., 2015; Uttal et al., Under Review).

Engineering schools, however, have chosen to assess spatial skills with the Revised Purdue Spatial Visualizations Test: Visualizations of Rotations (Revised PSVT: R) (Yoon, 2011), to determine whether or not students should be placed in a spatial development course. The Revised PSVT: R is considered an assessment of mental rotations, but some items require an offset revolution about the z-axis axis in addition to a 3D static rotation. The multiple manipulations can be thought of as a partial revolution (earth revolves around the sun across a season) combined with a rotation (earth rotating about its own axis). The increased number of operations necessary to determine a solution seems to suggest individuals should view the Revised PSVT: R as more difficult than other mental rotations assessments.

This study seeks to answer the question, *how does gender and spatial skill compare across object manipulation assessments?*

Frameworks

Lesions affecting the left side of the brain impair speech and other expressive functions as determined during the 1860s (Hegarty & Waller, 2004). Nearly a century later, figure and facial recognition deficits were found to be triggered by trauma afflicting the right side of the brain. These discoveries prompted the development of theories of separation—the disjunction between verbal and visual processing (Paivio, 2007). Specifically, Paivio's dual coding theory (DCT) (Paivio, 2007) and Baddeley's working memory model (WMM) (Baddeley, 2007) were established on the premise that verbal and nonverbal processing were distinct and independent from one another.

The following account describes what researchers know about how spatial processing is organized. Figure 2.1 illustrates the model's components beginning with Baddeley's WMM which delineates two systems (channels): the phonological loop and visuospatial sketchpad. Concurrent processing can occur across, but not within, channels like two lightbulbs connected in parallel. In other words, two tasks can occur simultaneously, only if each task is processed by a different channel. Two tasks cannot occur on the same channel at the same time. They can only occur in series, or one after the other (Sims & Hegarty, 1997). Dual task studies have provided empirical evidence to support the dissociation between verbal and nonverbal information processing. This is further reinforced by studies utilizing Positron Emission Tomography (PET) scans that assert different regions of the brain are activated by verbal and nonverbal tasks (Salmon et al., 1996).

According to cognitive psychology and neuroscience research, the sketchpad is composed of two independent components: the visual domain and the spatial domain (Kozhevnikov, 2015). The visual domain relates to an object's appearance that processes details about shape, color, texture, etc. within or across an image. Conversely, the spatial domain processes spatial relations in the form of static and dynamic object transformations from either an intrinsic or extrinsic perspective. Essentially, the visuospatial sketchpad is subdivided into two distinct elements just as the phonological loop (verbal) is separate from the visuospatial sketchpad (nonverbal).

Support for this view arises from differences in brain activation regions: ventral (visual domain) and dorsal (spatial domain)— as well as from findings from cognitive psychology. Hegarty and Kozhevnikov (1999) determined students, generally, used two strategies when solving word problems. They either produced schematic representations or created pictorial illustrations. Kozhevnikov, Hegarty, and Mayer (2002) found a bimodal split among visualizers when visual-spatial ability was assessed. This led to a study to compare how artists and scientists performed on visual-based and spatial-based assessments (Kozhevnikov, Kosslyn, & Shephard, 2005). Indeed, artists performed significantly better than scientists on a visual-based test (grain resolution) and scientists scored significantly higher on a spatial-based test (paper folding) than artists. This was further solidified by an investigation into abstract representations within the spatial-based domain with think-aloud protocols when participants (visual artists, physicists, and engineers) were asked to interpret kinematics graphs— abstract representations of motion (Kozhevnikov et al., 2005). High spatial visualizers (physicists and engineers) were able to create schematic representations of motion, and low spatial visualizers (visual artists) generated inaccurate pictorial representations. The spatial domain appears to be beneficial to the STEM domain.

Although spatial assessments have been utilized for a long time, the lack of theory has defocused and impeded progress in the area. Some attempt, over the years, has been made to categorize or organize the variety of spatial tests to connect with underlying spatial dichotomies like allocentric vs. egocentric and extrinsic vs. intrinsic. To add to the confusion, terminology overlapped and changed over time. Previously cited literature, in this paper, uses current terminology (as of the beginning of 2016) for the purpose of cohesiveness.

Recently, Uttal et al. (2013) developed an organizational system for spatial-based skills. The categories are represented as a four quadrant typology (See Figure 2.2). Intrinsic and extrinsic components are positioned along the x-axis with static and dynamic placed on the y-axis. Intrinsic refers to object description either holistically or as the sum of its parts while extrinsic signifies the relationship between objects or to a reference frame (Ganis & Kievit, 2015). Static denotes an object is fixed against the frame of reference and dynamic indicates an object or its frame of reference is moving.

Consequently, the four quadrants are intrinsic-static, intrinsic-dynamic, extrinsic-static, and extrinsic-dynamic. Figure 2.2 illustrates the four quadrant typology and provides sample spatial assessments as examples of each: Embedded Figures (Witkin et al., 1971), Water-Level (Inhelder, 2013), Mental Rotations (Vandenberg & Kuse, 1978), and Perspective-Taking (Hegarty & Waller, 2004).

This study investigates the intrinsic-dynamic portion of the spatial domain, also known as object manipulation. This segment is assumed to encompass both mental rotation and spatial visualization skills. Researchers (Newcombe & Shipley, 2015; Uttal, et al., 2013) believe mental rotation and spatial visualization are two separate object manipulations skills. Both skills rely on memory and processing components, however mental rotation tasks require less complex processing than spatial visualization tasks. Three mental rotations and three spatial visualization assessments, as determined by the extant literature, were utilized in this study.

Methods

Participants

Participants were purposely sampled using the following criteria: (1) an interest in engineering, (2) enrolled in an introductory AutoCAD™ class, and (3) an ethnically diverse group. All 433 participants (94 females and 339 males) represented typical students enrolled as introductory engineering majors at a particular college of engineering at a large southeastern university.

Assessments

Six short spatial assessments were chosen to measure two separate object manipulation skill types: mental rotation and spatial visualization. The mental rotation category included Card Rotations (CR) (Ekstrom, French, Harman, & Dermen, 1976) Cube Comparisons (CC) (Ekstrom et al., 1976), and the Revised PSVT: R (Yoon, 2011). Form Board (FB), Paper Folding (PF), and Surface Development (SD) formed the spatial visualization set (Ekstrom, et al., 1976). Cronbach alphas were calculated for each object manipulation assessment to approximate reliability (internal consistency).

The aforementioned assessments were chosen for comparison between the Revised PSVT: R and alternate object manipulation skill assessments. A required score of sixteen on the Revised PSVT: R is often the standard for avoiding placement in a spatial skill development course at colleges of engineering in the United States.

The overall research question in this investigation is, *how does gender and spatial skill level compare across object manipulation assessments?* Two sub-questions reflect specific aspects of the general question:

1. Do assessments of spatial skill level correlate with one another? If so, are the correlations significant?
2. What specific gender differences exist among first-year engineering students' spatial skill level?

Procedure

Data was collected across three consecutive semesters, not including the summer session. The same set of assessments, in the same order, were given to all students during normally scheduled class time for class credit. Some students arrived late to class and missed the first set of assessments, and a few chose not to participate in other assessments. This accounts for some of the variation in total number of participants for each test comparison. Those students who provided consent, per the university's internal review board policies, were included as participants in the study.

The CR test was removed from the third semester set of assessments. Instead, participants completed two additional assessments, unrelated to the current study, after the aforementioned order of assessments. Class time constraints limited the number of assessments administered per session.

Analysis

Both Excel™ and JMP® were utilized for all quantitative analysis, except when Excel was limited in functionality. Upon graphing the data collectively, and by gender, it was determined the data was not normally distributed. Therefore, Spearman's rank correlation was run to determine the relationship between each object manipulation assessment by gender. A Mann-Whitney U test was performed to determine level of significance between the medians of each spatial test across gender. Mean rank, sum or ranks, Chi-square values, and significance were calculated. The chi-square distribution was used as an approximation and Cohen's *d* represented the effect size.

Results

Table 2.1 displays Cronbach's alpha values for each object manipulation skill assessment utilized in this investigation. Values above .8 are acceptable because they fall within the "very good to excellent range" for internal consistency (reliability). The items within each assessment are uniform in measuring the same entity.

Assessment mean rank, sum of ranks, Chi-square values, significance levels, and effect sizes (Cohen's *d*) are shown for each object manipulation skill in Table 2.2. Only the results from the Revised PSVT: R spatial assessment suggested gender difference. The Cohen's *d* value (0.53), as shown with an asterisk in Table 2.2, is consistent with findings from recently published meta-analysis data (Cohen's *d* = 0.57) (Maeda & Yoon, 2013).

Table 2.3 displays the Spearman's rank correlation coefficients for each test comparison. The asterisks, next to each coefficient, indicate the level of significance as noted below the table. All male Spearman's rank correlation coefficients were statistically significant at the $p < .001$ level. Most Spearman's rank correlation coefficients were at the moderate level with a few exceptions (CC-FB, CR-FB, CR-PF, and CC-Revised PSVT: R) at the weak level. Those with weak correlations were comparisons between mental rotations assessments (CR, CC, and Revised PSVT: R) and spatial visualization (FB, PF, and SD). Male data suggested that the Revised PSVT: R data was significantly moderately correlated to spatial visualization skill level. However, the CC-Revised PSVT: R (mental rotations) relationship indicated a weak correlation.

Female data suggested a distinction between spatial visualization and mental rotations spatial skill level. Correlations between FB, PF, and SD (spatial visualization) are weak to moderate, but significant. In addition, the CR-CC (mental rotations) significant correlation is weak. When spatial visualization and mental rotations spatial skill level were compared, there were no significant correlations. The Revised PSVT: R has no significant correlations with "mental rotations", however FB and SD (spatial visualization) were significantly moderately correlated with the Revised PSVT: R. PF-Revised PSVT: R is moderately correlated, but not significant ($p = .063$).

Discussion and Implications

This study examined the spatial skill level of students interested in the engineering disciplines. In particular, intrinsic-dynamic (object manipulation) skills were assessed among first-year students enrolled in a college of engineering at a large southeastern university. Researchers (Newcombe & Shipley, 2015; Uttal et al., 2013) suggest that intrinsic-dynamic skills are divided into two independent categories: mental rotation and spatial visualization.

The Revised PSVT: R was the only assessment to indicate a significant difference between genders and the results were very similar to a meta-analysis performed across previously published data (Maeda & Yoon, 2013). The effect size (Cohen's *d*) in this investigation was 0.53 and that of the meta-analysis was 0.57.

These results support and refute previous studies (Kozhevnikov et al., 2002; Linn & Peterson, 1985) that found males performed better on mental rotations and spatial visualization tests than females. Findings, in this study, show no gender difference for CR, CC, (mental rotations) FB, PF, or SD (spatial visualization) assessments; however, the participant sample was defined as individuals interested in engineering. Possibly, students drawn to engineering have strengths consistent with those utilized by the engineering community of practice (ECoP) (Lave & Wenger, 1991). For example, those who enter the visual arts tend to be able to sketch, paint, or have a sense of color. Participating in activities that align with a commensurate skill set may make it easier to join, acclimate, and attain a sense of belonging to the group.

The Revised PSVT: R correlated more closely, for both males and females, with assessments of spatial visualization (FB, PF, and SD) (Ekstrom et al., 1976) than mental rotation—the category most associated with the Revised PSVT: R according the extant literature. Mental rotation and spatial visualization are believed to require two steps: memory and processing (Kaufmann, 2007). The memory component, mediated by spatial short term memory (STM) (Cowan, 2008), allows individuals to temporarily store images. In the case of the Revised PSVT: R assessment, visual details of the chiseled cube must be maintained while the brain processes, by the spatial working memory (SWM) (Cowan, 2008), how to rotate the image to be in agreement with the specified visual-spatial analogy.

As previously stated, mental rotation requires an individual to mentally rotate an image, whether in 2D or 3D space. The Revised PSVT: R raises mental rotation to another level with the addition of a secondary maneuver, coupled with an analogy of a set of spatial manipulations represented by another cube. Conceivably, mental rotation in its most complex state converges on the processes that underlie spatial visualization. One might ask, could mental rotations be a lower level skill, or perhaps subsumed by spatial visualization?

Alternatively, if mental rotation and spatial visualization are indeed two separate constructs, the Revised PSVT: R could tap into both mental rotation and spatial visualization skill level. The CC-Revised PSVT: R correlations were $r = .13$ and $r = .33^{***}$, respectively, for females and males. Both groups (males and females) performed well and similarly on the CC assessment. However, males scored significantly higher on the Revised PSVT: R than females. Both male and female engineering students were able to carry out mental rotation and spatial visualization tasks separately. However, females had difficulty with the Revised PSVT: R. It is possible that females may find it difficult to process higher order tasks that require both mental rotation and spatial visualization processing either simultaneously or in tandem within the same task. This possibility could account for the statistically significant weak and moderate correlations across all male test comparisons and the inconsistent nature of female data.

Is it possible that the visual properties of the object are detailed enough to warrant visual system processing? Could both visual and spatial systems be necessary to correctly answer Revised PSVT: R items? (Wood, 2011). See Figure 2.1 for the placement of the visual system on the model of visual-spatial skills. The visual system is more closely aligned with visual artists' skills because details are important when representing objects. The spatial system is related to the space between objects and their relation to one another. Perhaps the detail contained within the objects of the Revised PSVT: R require skills from the visual system. Or conversely, visual processes are being used and taking up space within working memory that limit spatial processing. Kaufman (2007) suggests a difference may exist is the capacity of working memory among gender. Males tend to experience more spatial activities than females because of an early interest in activities that enhance spatial skills. This experience may have expanded working memory capacity to process spatial tasks.

How are individuals creating interventions to know which skills students possess: mental rotation, spatial visualization, neither, both, etc., when the Revised PSVT: R is the sole assessment used to determine object manipulation spatial skill level? Does a low score on the Revised PSVT: R imply a student has difficulty with spatial short term memory, spatial working memory, or both? Diagnosing this with the current available resources is problematic. Perhaps a low score on the Revised PSVT: R should be followed by an assessment of lower level processing tasks to determine individual student difficulties.

Summary

Six assessments of mental rotations and spatial visualization revealed a significant difference between gender on the Revised PSVT: R assessment only. This is consistent with previous findings (Maeda & Yoon, 2013). When participant data was separated by gender and compared across assessments a Spearman's rank correlation test uncovered significantly moderate and strong correlations among mental rotations and spatial visualization assessments for male participants. Data collected from female participants indicated significant weak to moderate correlations between the Revised PSVT: R assessment and other assessments of spatial visualization, except between PF and the Revised PSVT: R.

Limitations

There are two main limitations of this study: no CR-Revised PSVT: R comparison data was collected and other spatial tests could have been administered. CR and Revised PSVT: R data could not be collected at the same time due to time constraints driven by the fifty-minute class period. Other tests could have been utilized; however, at the expense of decreased sample size for each comparison. Since the female population in engineering courses is generally smaller than the male population, this was not an appropriate option.

Further Studies

The Revised PSVT: R is not the only complex mental rotations assessment. A comparison between the Revised PSVT: R and Vandenberg and Kuse's (1978) Mental Rotations Test could prove informative. Kaufman (2007) determined that the Mental Rotations Test had a unique variance associated with it that did not directly connect with memory storage of an image. Investigation into higher-level forms of what are currently defined as mental rotations tests may disentangle the underlying processes associated with solving assessment items. Are these actually tests of mental rotation, assessments of mental rotation and spatial visualization, or neither? Is there a visual component within the spatial component? Does spatial short term memory and/or spatial working memory have anything to do with it?

Engineering education literature has focused on mental rotation skills as important to the field, but it is important to ask the question, what about other spatial skills? Engineering is a diverse field of study. Does domain specificity play a role in the types of spatial skills necessary for each particular field? Does a chemical engineer rely on the same kinds of spatial skills as an industrial engineer? As interdisciplinary engineering (biomedical, biological, environmental, etc.), fields emerge, in what ways do those fields rely on spatial skills? What spatial skills might be included in a core set of skills common to all engineering fields?

In addition, do measures of spatial skill level relate to abstract representations? Current tests of spatial skill level are concrete. The visualizations are of real tangible objects from different orientations. Process diagrams, however, are schematics—abstractions of tangible objects and processes. Perhaps assessing experts from each engineering domain could inform the types of spatial skills necessary for different engineering fields. For example, an engineer who predominately works with computer aided design software to design fixtures probably uses a different set of spatial skills than does a process or quality control engineer.

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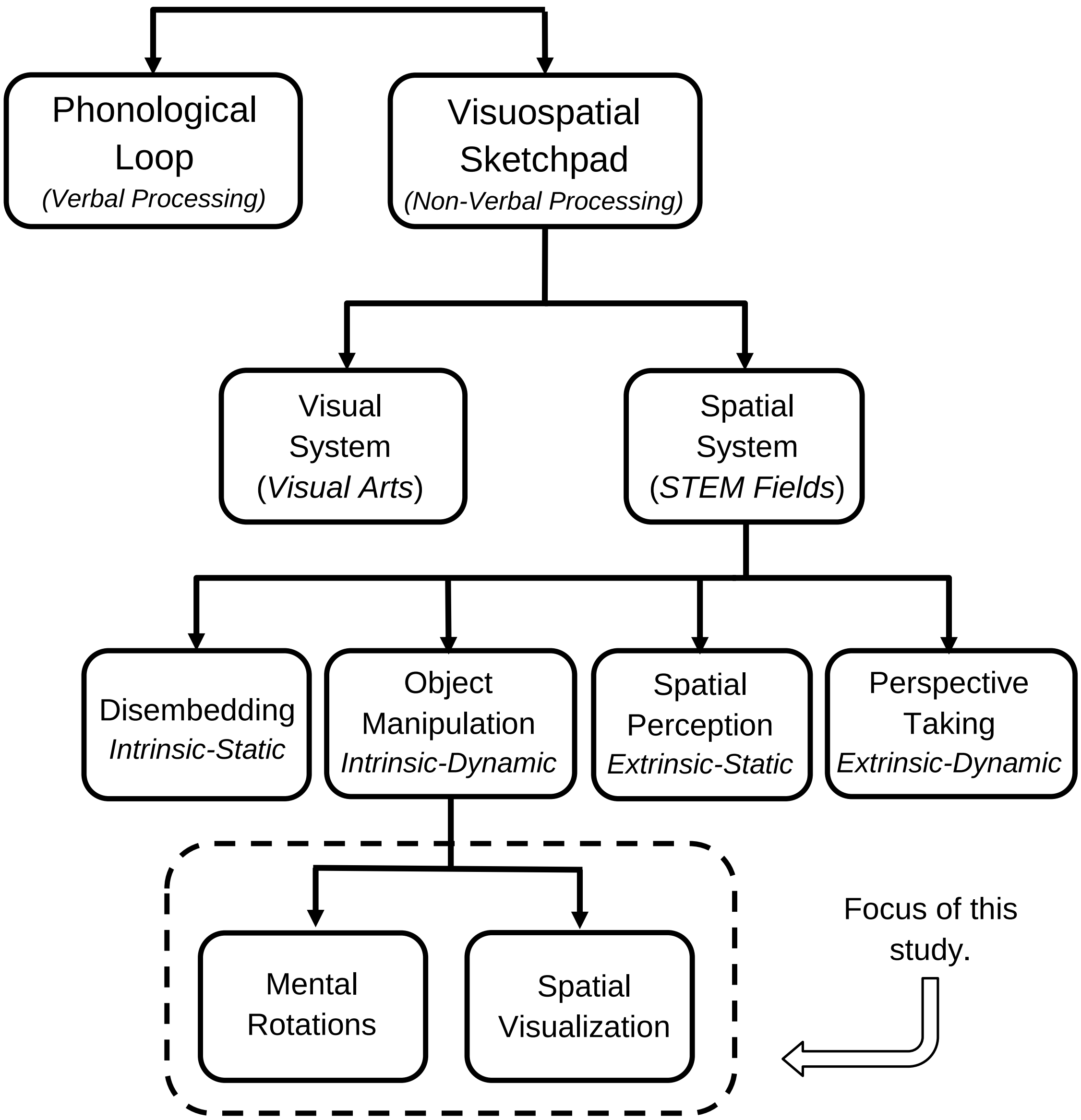

Figure 2.1. Model of visual-spatial skills.

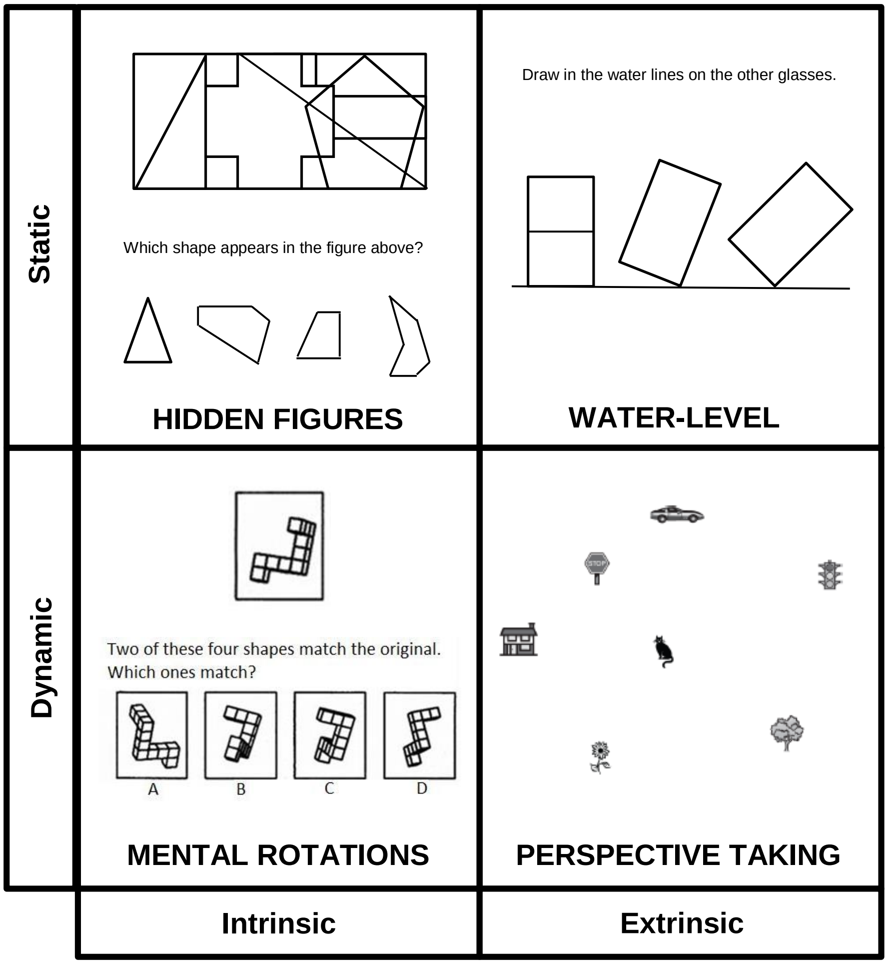

Figure 2.2. Typology aligned with sample spatial skill assessments. Adapted from Uttal et al. (2013) and Okamoto et al. (2015).

Table 2.1

Cronbach's α for Each Spatial Assessment

CR	CC	FB	PF	SD	Revised PSVT: R
0.99	0.85	0.91	0.83	0.93	0.89

Table 2.2

Mann-Whitney U Test Results Across Gender

	N	Median Rank	Sum of Ranks	χ^2	Test *p*	*d*
CR						
Male	203	66.3	8326	0.01	.92	0.0072
Female	61	66.3	26919			
CC						
Male	330	61.9	69748	0.015	.9	0.022
Female	94	57.1	19928			
Revised PSVT: R						
Male	129	60	10255.5	7.99	.0047	0.53
Female	29	50	2305			
FB						
Male	325	50	68741	0.406	.53	0.062
Female	92	50	18830			
PF						
Male	334	70	71262	3.6	.059	0.19
Female	94	60	20116			
SD						
Male	338	65	72792	0.57	.33	0.065
Female	94	63.3	20304			

Table 2.3

Spearman's Rank Correlation Matrix of Spatial Assessment Scores for Males and Females

Measure	1	2	3	4	5	6
Males						
1. CR						
2. CC	.50**					
3. Revised PSVT: R	-	.33***				
4. FB	.38***	.25***	.45***			
5. PF	.39***	.44***	.45***	.41***		
6. SD	.42***	.43***	.54***	.43***	.60***	
Females						
1. CR						
2. CC	.30*					
3. Revised PSVT: R	-	.13				
4. FB	.16	-.03	.48**			
5. PF	.28*	.2	.48	.26*		
6. SD	.01	.15	.47**	.35***	.42***	

*Note: *p < .05, **p < .01, ***p < .001*

CHAPTER 3

DISENTANGLING STUDENT CONCEPTIONS OF CREATIVITY IN PRODUCT DESIGN AND THE DESIGN PROCESS[2]

[2] Murray, J. K. To be submitted *Journal of the Learning Sciences.*

Abstract

Implicit theories of creativity in engineering, specifically in regard to product design and the design process, may or may not align with coexisting explicit theories of creativity in engineering. Implicit theories are personal conceptions of explicit theories—theories that arise from research in a particular domain. All forms of experience, both past and present, shape views about aspects of the physical and social world. The following chapter explores what creativity in engineering means to first-year prospective engineering students at a large southeastern university. The exploratory qualitative investigation utilized interviews, open-ended questionnaires, and participant-created product designs to answer the overarching research question: *In what ways do inbound and peripheral legitimate participants the field of engineering, conceptualize creativity within product design and the design process?* Findings revealed varying conceptions of creativity in product design and the design process. In some cases, students' views diverged rather than converged on explicit theories of creativity. Participants considered creativity a dichotomy between art and science, the blending of art and science in engineering, and as implicit problem solving. A few participants treated creativity as a sub-problem within the product design task. Creativity in the design process was predominately expressed as a single non-recursive procedure with a focus on initial ideas, prematurely selected. An awareness of student conceptions enables educators to be responsive to student understandings through careful selection or creation of educative experiences that prompt transformative learning experiences.

Introduction

Engineering education, a relatively new education research area, has begun to investigate creativity and its relation to design. Particularly, design researchers have compared experts to novices (Atman et al., 1999, 2007; Crismond, 2001; Daly et al., 2012), investigated associative strategies (Beaty et al., 2014; Cardoso & Badke-Schaub, 2011b; Casakin, 2004; 2007; 2011; Hey et al., 2008; Shah, et al., 2012;), focused on student use of divergent thinking (Bailey, 2008; Cardoso & Badke-Schaub, 2011a), examined divergent and convergent practices in the engineering curriculum (Daly, et al., 2014), and created divergent and convergent thinking assessments (Charyton & Merrill, 2009; Charyton , Jagacinski, Merill, Clifton, & DeDios, 2011).

In general, these researchers focused on the early phases of the design process because these phases require more creative effort than later phases of the process. However, all phases of the design process share components of divergent and convergent thinking. The design processes used in engineering overlap with many features of the creative problem solving (CPS) process (Howard, Culley, & Dekoninck, 2008). Design, however, is domain-specific and CPS is domain-general.

The field of creativity has a rich history of research in CPS. Alex Osborn, of the advertising industry and inventor of the brainstorming technique, developed the first version of CPS in the mid-1950s (Isaksen, Dorval, Noller, & Firestien, 1993). The CPS method was presented in his 1953 book *Applied Imagination* for the purpose of “dealing with challenges and opportunities which are novel, ambiguous, or complex” (Isakesen, Dorval, Noller & Firestien, 1993, p.155). Since then CPS has advanced to a multiphase recursive process that blends divergent and convergent thinking to stimulate creative thinking.

Functional creativity, the idea that function is more important than originality in engineering design, was coined by Cropley and Cropley (2005) to differentiate creativity in engineering from creativity in art. Although tacitly accepted by the field of engineering, students and novices may have difficulty with an accurate interpretation of functional creativity.

Typically, students are introduced to academics (language arts, mathematics, social studies, and science) and the arts (physical education, music, and performing and visual arts) during the K-12 years. Exposure to different fields of study, both formally and informally, permit individuals to encounter what they perceive to be relevant practices significant to the particular field. Students, in turn, internalize these experiences and form conceptions about the world (Pintrich, Marx, & Boyle, 1993).

Individuals are exposed, at an early age, to art and its interpretation of creativity; however, until recently the practice of engineering has not been part of the K-12 curriculum. What do prospective engineers know about creativity in engineering? Implicit theories describe personal constructions that may or may not be consistent with explicit theories (Sternberg, Conway, Ketron, & Bernstein, 1981) like functional creativity. This study seeks to understand how post-secondary introductory engineering students conceptualize creativity in design and the design process.

Identification of other’s conceptions is the first step towards changing individuals’ conceptions (Pintrich et al., 1993). Individuals choose a path in life based on preconceived notions about what it is they want to do. Some will enter college as engineering majors, not knowing if their conception is consistent with the practices of the field. Engineering students are positioned as legitimate participant learners, peripheral to the engineering community of practice (Lave & Wenger, 1991). Past and present experiences necessarily influence, clarify, and redefine students' conceptions of the practice of engineering.

Instructors have opportunities to construct learning experiences and alter student thinking through educative experiences (Dewey, 1938) that may support transformative experiences (Pugh, 2011) which ultimately expands students' repertoires of practice (Rogoff et al., 2007). Without consideration for student conceptions, learning experiences may not foster transformative experiences that shift conceptions toward a common view consistent with an engineering community of practice (ECoP).

Review of the Literature

Creativity in Design

Creative engineering design research began about twenty years ago with most studies occurring in the past ten years. An initial, but prevailing approach, focused on comparisons between students and experts, as well as, between freshman and senior level students. Crismond (2001) studied the design process utilized by students and experts. He observed that novices did not connect relevant science concepts with the design task, as experts did. Furthermore, Atman et al. (1999) discovered seniors generated more questions about specific facets of the design task than first-year college students did, in an effort to frame the problem. Seniors contemplated more possibilities in comparison to freshman and therefore produced better products. When students were contrasted with experts, Atman et al. (2007) determined experts required more time, overall, to complete the design task. Specifically, experts budgeted additional time for the initial stages of design: problem definition and information gathering. Experts were intentionally more deliberate during the initial planning stages of design and that is why they required more time.

Many studies have focused on divergent and convergent thinking processes, specifically, across the design process. Divergent thinking refers to the production of many ideas where judgment is prohibited. Upon conclusion of idea generation, convergent thinking processes enable selection of appropriate ideas based on affordances and constraints of each idea. Analytical skills Creativity requires both divergent and convergent thinking processes (Runco, 2010). Runco, Dow, and Smith (2006) suggested that knowledge and experience enhance individuals' ability to engage in divergent thinking tasks.

Researchers have investigated design by seeking to understand how divergent and convergent thinking skills were utilized in design. Ideation and evaluation in tandem has proven to result in more creative products. Daly et al. (2012) concentrated on student versus expert ideation during the problem definition stage. Given a particular design task, experts on average utilized seventeen heuristics while students employed twelve. Daly et al. (2014) also interviewed design instructors about how they incorporated aspects of divergent and convergent thinking into design courses. There was an emphasis placed on convergent aspects such as analyzing, reorganizing, and evaluating designs. Instructors stated the importance and value of generating multiple ideas, however it was not explicitly stated or assessed so students did not view it as important.

Charyton and Merril (2009) were frustrated with the lack of ill-structured problem solving in engineering curricula. To assess student problem solving skills they developed the Creative Engineering Design Assessment (CEDA)— a collection of divergent and convergent thinking skills specifically related to engineering. Its intended purpose was to measure changes in skills within and across engineering courses, and specifically after interventions. Charyton et al. (2011) later revised and republished the CEDA.

In another study an intervention was added to the design curriculum centering on the early stages of design—processes that focused on divergent thinking. Findings revealed students were not able to provide adequate problem definitions even after a two-part lesson was completed, separated by a design challenge (Baily, 2008). Other researchers tried to be more specific, by focusing on one particular skill at a time. For example, in one investigation researchers exposed industrial design students to pictorial representations of currently available designs which ultimately caused design fixation. In comparison to the control group, students focused on specific attributes seen in visual representations (Cardoso & Badke-Schaub, 2011a). Results suggest realistic looking pictures increased fixation in comparison to stick-figure drawings.

Other approaches examined associative strategies, particularly those that utilized analogies or metaphors to map conceptual or structural features across domains. Casakin's work has focused on the use of metaphor in design. His early work addressed the use of metaphor throughout student design (Casakin, 2004). The abstract concept improved design in the initial stage, particularly with problem definition statements and discernment of requirements, but metaphor did not translate into concrete aspects of the physical design. Again, Casakin (2007) tried to implement metaphor into design, but found students still could not use metaphors to provide concrete features to make designs useful or original. He suggested students need more practice with metaphor before it could become useful.

Hey, Linsey, Agogino, and Wood (2008) concentrated on analogies associated with student design conceptions. Students were given an example like a device to fold laundry and told to generate ideas for a similar, but novel, device of the same purpose. Researchers looked at the analogical distance between student ideas. Paper folding or metal folding were considered local analogies while rolling a cigarette was deemed a remote analogy. The more distant the analogy, the more creative the association.

Implicit Theories of Creativity

Implicit theories unveil personal beliefs about concepts, ideas, or practice. Initial interest in implicit theories stemmed from theories of intelligence. Two common implicit theories of intelligence are the theory of incremental change and the entity theorem. The former theory views individual ability as a dynamic element—one that is malleable and capable of change. The latter assumes individuals have a fixed ability. Student and teacher implicit theories of intelligence affect student motivation and teachers' practice (Jones, Bryant, Snyder, & Malone, 2012).

Likewise, implicit theories exist in relation to an interpretation of creativity. Runco and Johnson (2002) discovered that both Indian and U.S. parents converged on desirable and undesirable characteristics of creativity, but these views were inconsistent with explicit theories of creativity. A survey of Hong Kong teachers revealed teachers were in closer agreement on uncreative characteristics of individuals than creative explicit theories (Chan & Chan, 1999). Artists' implicit theories implied creativity was different in art in comparison to science (Runco & Bahleda, 1986). Artists viewed scientific creative as thorough and artistic creativity as expressive. More recently, Tsai (2016) asked art and design students to characterize creativity. They described creativity as originality, novelty, etc., but left out "usefulness".

When Portillo (2002) examined the nature of creativity across several disciplines (interior design, architecture, landscape design, and engineering) a core set of similarities emerged from the data. However, each discipline had its own cluster of specific traits unique to the respective domain.

Frameworks

Situated Learning

The situative perspective of learning views learning as a practice-based theory where experience facilitates learning and learning facilitates experience. In this way, learning is influenced by the environment, the people in it, and the interaction between the two (Greeno, 1998). At an early age children are exposed to regular patterns of social interaction with family, neighbors, and school. Eventually experience broadens with age as individuals engage with other facets of the world. Experience with communities; social, professional, or academic formal and informal organizations, expose practices central to their functioning. Engagement with each community shapes how individuals learn to assimilate, accommodate, and reject new information (Chinn & Brewer, 1993). These experiences increase individuals' repertoire of practice with the addition of new knowledge and understandings obtained through participation in communities of practice (CoP).

The participants in the current study have an accumulated repertoire of practice they used in order to navigate the world. They selectively choose which practices to utilize in any given situation. The participants had an interest in engineering because they were enrolled as engineering majors in college. There was an interest in being a part of the engineering community based on what they believed they knew about engineering. The question is, did what they know about engineering align with the ECoP?

Problem solving is central to the practice of all engineering disciplines. Creative problem solving (CPS) manifests in different ways across specific tasks and disciplines. The next section outlines the CPS model.

Creative Problem Solving

Brophy (1998) described creative behavior as pursuing possibilities to achieve an outcome. When applied to problems—gaps between present situations and feasible solutions (Treffinger, Selby, & Isaksen, 2008), this became known as CPS. The creative research community has elaborated on the definition of CPS for more than sixty years to integrate divergent and convergent thinking processes for the purpose of strengthening the development of CPS skills. CPS differs from general problem solving because general problem solving uses prescribed algorithms, specific to the type of problem, to solve well-defined problems (Treffinger et al., 2008). Ambiguous, ill-defined problems and tasks require CPS methods that rely on creative thought and inventiveness because no algorithm exists (Runco, 2008; Treffinger et al., 2008).

The CPS model emphasizes divergent thinking skills at the beginning of the process and convergent thinking skills toward the end. Basadur (1995) considers the basic model of CPS to have three stages: problem finding, problem solving, and solution implementation. Problem finding stresses the generation of many ideas for the identification of sub-problems to the overarching problem, exploring data, and framing problems. Problem solving develops solutions through refinement after analysis. And lastly, solution implementation is predominately carrying out the plan, perhaps with modifications.

Studies have shown (Brophy, 1998) that students who concentrated on problem finding aspects of the CPS model have become successful artists as well as scientists. Although the CPS model is a domain general process, technical fields depend on robust domain-general and specific knowledge to produce creative solutions (Brophy, 1998; Feist, 2005).

Making associations that draw upon cross-domain content to form new ideas or analogies is the basis of the associative theory of creativity. The theory states that associations between two or more elements are constructed around one or more common features as a result of the divergent thinking process.

Associative Theory of Creativity

Where do associations come from? Prior knowledge in the form of formal and informal educational experiences, as well as personal experiences, are crucial to developing new knowledge. This knowledge, acquired explicitly or implicitly, has the capacity to be connected. Requisite knowledge transfers and combines with other requisite and/or new knowledge to configure associations among elements (Mednick, 1962; Gabora, 2005).

For example, an engineer could not design a safe bridge without knowledge of all forces acting upon the bridge, and interactions among bridge components at a specific construction site. A suspension bridge was a creative invention. Supporting bridges from above with cables rather than from below with a series of under mount supports was novel at the time of its invention. The inspiration could have been from a small draw-bridge that crossed a castle boat and a simple beam bridge.

Gabora's (2005) honing theory of creativity expands on the use of prior knowledge in the creation of new associations. It seems logical one needs to know something about a topic in order to make connections between two or more topics. However, there are exceptions to this rule. Within the domain of physics, physicists often make discoveries early in their careers (Brophy, 1998). On one hand, Mednick (1962) assigned the term low flat-associative hierarchy to describe this phenomenon because low requisite knowledge is necessary to draw connections among disparate elements. In essence, one may not be limited by what they know. On the other hand, steep-deviant associative hierarchies, as exemplified by one who makes a creative connection and clings to that same idea, are not as creative. Sometimes people are successful with this type of creativity. To illustrate this point, think about the creators and/or writers of the 1970s and 1980s hit show, *Three's Company*. Although the premise was new for a television sitcom of its time, the plot was similar each week—a circumstance based on lack of or mis-communication among roommates and other residents in the apartment complex.

The associative theory states that original thoughts depend on remoteness of elements while still maintaining a common thread. The more distant ideas are from one another the more original the new idea becomes. Higher levels of creativity are consistent with more remote connections formed between ideas.

Functional Creativity

Cropley and Cropley (2005) introduced the concept of *functional creativity* to describe and encompass forms of creativity within the engineering domain. The concept developed out of a dissatisfaction with the perceived notion, implied by the creative community, that originality was favored over usefulness. The phrase *functional creativity* refers to the importance of usefulness above originality in engineering product design. Within the domain of engineering, functionality is paramount. Product development often includes a set of functional requirements (criteria and specifications).

Elegance and genesis are placed behind functionality and originality, in that order, to complete the four dimensions of functional creativity. At a minimum, products, processes, systems, and services must be both functional and original to qualify for *functional creativity* status. Elegance is the *why didn't I think of that?* response to solutions. Often this dimension is met with a ho-hum reaction because it is understated. Observers frequently perceive products of this nature as not so creative. An example is a child's summertime pool toy- the noodle. The noodle works on the principle of low density buoyant foam and provides children enjoyment as a floatation device. It is simple, but perceived as simplistic. Genesis, however, encompasses solutions that are revolutionizing. This dimension changes the course of the field. The steam engine is an example, as its technology appeared in trains, boats, and cars throughout history.

The frameworks provided the foundation for an investigation into prospective engineers' implicit theories of creativity in engineering. The context, research design, methods, and analysis are described below.

Methods

Research Design

This exploratory qualitative study (Bazeley, 2013) utilized a multi-method approach to understand first-year engineering students' views of creativity in engineering. Methods used included interviews, an open-ended questionnaire, and a product design task (see Appendix A) to answer the research questions. The overarching research question was: *In what ways do inbound and peripheral legitimate participants to the field of engineering, conceptualize creativity within product design and the design process?* The three sub-research questions were as follows:

1. How is creativity perceived in product design?
2. What creative approaches and elements emerged in product design?
3. How are components of the design process employed during product design?

A literature review of research in engineering education, design, and creativity revealed a lack of studies about inbound and peripheral legitimate participants' implicit theories about repertoires of engineering practice in ECoP. To answer the first sub-research question, all data sources were utilized to investigate participant thoughts about engineering creativity. Figure 3.1 depicts a representation that organizes how creativity was envisioned through the generation of a tangible product in this investigation. In addition, quotes were used as evidence to articulate participant views of creativity.

Figure 3.2 depicts the creative strategies utilized, as stated by participants, to focus the design while Figure 3.3 represents the categories and combinations of elemental design as observed in final product designs. The two visual representations (Figures 3.2 and 3.3) are supported by written descriptions to satisfy sub-research question two.

The last sub-question relied solely on participants' open-ended questionnaire responses. An analysis characterized how participants carried out the design process as shown in Figure 3.4.

Context and Data Collection

Participants were purposively selected and enrolled in an AutoCAD™ course within a college of engineering at a large southeastern university. In general, the AutoCAD™ course served as a prerequisite to other engineering science and engineering design courses. Most participants were in their first year at this university, however other participants had switched majors and entered the college of engineering with credits that advanced them above freshman status.

The research design was approved by the university's Internal Review Board (IRB) and students were provided with a consent form. The researcher informed students that participation in the study was purely voluntary. Then students were given a design task as an assignment to do for homework. The design task was selected to provide students an opportunity to engineer a product that was appropriate in subject matter content knowledge level and consistent with engineering practice. Limiting material use (constraints) and providing product purpose (design criteria) enabled participants to identify and generate sub-problems contained within the larger issue represented an authentic design task. In addition, participants prepared design drawings to express product specifications. All students who completed the design task received participation credit from the instructor for the project. Only those students who provided formal written consent were added to the study.

Visual data, in the form of drawings and final product design photos, were collected to reveal a different level of participant experience (Gauntlett, 2007) with design. Interviews and written description privilege language as an ultimate mode of communication (Bagnoli, 2009); however, all forms of knowledge cannot be simplified to vernacular (Eisner, 2008). The final products are a way for participants to express themselves and display autonomy in the choices they make (Allen, 1958).

In total 155 participants (47 F and 108 M), over three semesters, volunteered to be part of the study and provided design projects for the study. The design task required participants to design a package from two 12 x 12 inch pieces of cardstock to hold six crayons and a Post-it™ notepad. Participants were directed to create one package that was both functional and creative in its design. No specifics were given to elaborate on the words “functional” and “creative”.

Participants answered questions about design inspiration, creative elements of design, and the design process in regard to the way they completed the design task. After physical product designs, questionnaires, and drawings were submitted, students had the opportunity to talk with researchers about their product design. Six participants (convenience sample) received twenty dollars for volunteering their time to interview.

Analytic Processes

Data analysis was managed with thematic analysis and a hybrid approach based on both inductive and deductive coding (Fereday & Muir-Cochrane, 2006) of interview transcripts and open-ended questionnaires. The focus was on “data driven” or emergent codes, however “theory driven” or a priori codes initially focused the design of the investigation (Guest, MacQueen, & Namey, 2011).

Interview transcripts were produced from audio files, student drawings and written responses were scanned, and photos were taken of student projects. All data were collated into a single MS Word® document and converted into a PDF file for each participant. Every file was uploaded to Atlas.ti (Scientific Software Development, 2011) as an individual primary document. Each document was read and reread to obtain a holistic sense of the data as well as to acquire a feel for the individual participants.

The first and second round of coding ensued with exploratory and elemental methods (Saldaña, 2015). Holistic coding: coding of large chucks of data, and provisional coding: coding based on a preliminary set of codes generated from initial observations of data were applied to the primary documents. A deeper look at the data required structural, descriptive, and process coding. For example, the set of structural codes: package as Chinese take-out container, package as CD holder, package as planner, etc., eventually became the category “package as everyday object”. Descriptive codes labeled features (*open fit, resource limitation, hand drawn*, etc.) and process codes denoted action (*sketching, constructed, modified*, etc.).

Following this coding process, codes were then lumped to create categories. Within Atlas.ti that means creating code families. For example, the category “factors imposed by designer" combined seventeen codes such as *minimize material use, design for children,* and *separation component*. Then categories were either united, remained, or were promoted to the rank of theme. To answer the research questions, themes were connected to other themes and categories to represent the data holistically. At this phase MS Excel® was utilized to compare frequencies between themes and categories to justify relationships. For instance, the theme ***Modifications*** was connected to the category "limited resources" (72%) and the themes ***Multiple Designs*** (88%) and ***Ideation*** (60%), because participants who generated multiple ideas and designs modified their package designs because they expressed limitations of time and resources (the amount of cardstock given).

The drawings and product photos as visual data sources were analyzed differently. Predominately, a priori coding was applied to photos with a qualitative content analysis (Rose, 2012). An emphasis was placed on creative elements of final design photos and spatial elements within product drawings.

Findings

Three sub-research questions focused, distilled, and supported the overarching research question: *In what ways do inbound and peripheral legitimate participants to the field of engineering, conceptualize creativity within product design and the design process?* The findings are imparted, separately, with a section devoted to each sub-research question.

RQ 1: How is creativity perceived in product design?

Participants had varied conceptions about what it meant to be creative. Many initially described the field of art as creative, but considered creativity to be immersed within all fields, just in different ways. Some had difficulty articulating the role of creativity in engineering and/or design. The following response, by Hailey, represented a characteristic reply to the question, “What is creativity?”

> O.k., well usually I think of creativity I think of more of the arts than like the sciences and math because in the sciences and math there is like one right answer and one way to do things. When it comes to like art, paint, and drawing that’s more like the creative aspect, but now that I’ve taken more engineering classes I also started to realize that, like, there’s much more ways to do things within that. So, I think, like, that’s where creativity blends in with the sciences. But, I guess, like, creativity for me is like ‘thinking outside the box’. I know that’s kind of, like, cliché, but thinking of other ways to improve your design or project in the sense of engineering. (25 – 33)

Engineering creativity was portrayed in a slightly different way, by James, as “’thinking outside the box’…just being able to look at something in a way no one else would look at it…just like not always taking something at face value, or doing it the easiest way” (32 – 36). Mark reiterated and clarified what the previous participants stated in the following: “I feel like creativity is just like trying to do something original, um, kind of not necessarily… like seeing a problem and solving it in your own way. As opposed to looking for something that’s like already made” (32 – 34). James and Hailey indirectly expressed thoughts of originality and problem solving while Mark was able to articulate it clearly.

Jessica stated, “In the world of engineering creativity, [creativity is] not as stressed as it is in other industries. I feel like creativity in other industries is a lot more defined” (28 – 29). She added, in the quote below, a definition of creativity that situates herself within the creative continuum. She identifies with creativity as problem solving, but not creativity as art.

> I kind of think of creativity as more artsy stuff, but in that sense of a definition I’m not really creative. I’m better at finding the best way to solve a problem that might not be by a normal means, but more like a concrete creativity. (21 – 24)

For all participants, functionality was as important or more important than creativity in the design of packages. Hailey struggled with knowing concretely what creativity was within art, but not being certain about what it meant to be creative in engineering. She alluded to the possibility of decorating her box to add a creative element, however, that was clearly not what she wanted to do. She recognized that the separation element solves a problem, but she could not quite link the word or definition of creativity to problem solving. This is what Hailey said:

> I think I definitely did focus more on functionality than I did creativity. When I think of how to make something creative I usually think of like the design of it. And so I would have like decorated the box, to be honest, to be creative. But, I guess, like, the separation between the two was the way I was thinking of like trying to think of a different way to, like, store more things. Cause, like, usually a pencil case is, like, you just throw everything in there. Um, but this is like more separated. (38 – 44)

Quotes from Hailey, James, Jessica, and Mark illuminated how participants thought about creativity. These views were collected from portions of the written responses participants submitted along with physical models and interviews conducted a few weeks after package completion. Figure 3.1 describes the outcome space; the ways participants perceived functional creativity as observed through the design of a package. Function was placed to the left because all participants considered functionality an important aspect of *functional creativity*. The position of “function” in Figure 3.1 does not imply it was more important than the other elements within the figure; it simply means all participants valued function.

Implicit problem solving referred to a myriad of possibilities participants came up with to solve an ill-defined problem—one that was not explicitly stated. This is representative of problem finding in the CPS model. For example, many participants chose to incorporate a separation mechanism between the crayons and notepad to prevent crayons or crayon shavings from soiling the notepad. Elegance, another element in Figure 3.1 is an additional creative feature beyond functional creativity elements (function and originality). See the framework section for further description of elegance. The last component on Figure 3.1 is aesthetics; indicative of decorative feature(s) more closely aligned with an artistic approach to creativity.

Participant conceptions are represented by each branch of Figure 3.1, starting on the left spanning across to the right. Individuals within any group prioritized and weighted each element differently in comparison to other participants in the group. For instance, within the function and implicit problem solving group, some participants may have emphasized function over implicit problem solving while others chose to focus on implicit problem solving over function.

The first group was defined by function and aesthetics or just function. Simpler more functional packages were placed in this category. Designs included basic shaped packages which may or may not have had some ornamentation.

The second cluster valued function and implicit problems solving. This group was the largest and encompassed a wide variety of functional categories from loosely held components to carefully thought out placements for objects. Participants considered separate compartments, separation mechanisms, different types of fasters, and multiple configurations, to name just a few design elements.

The third collection favored function, implicit problem solving, and aesthetics. An example within this group included packages that loosely fit the crayons and pad into an embellished container with a novel enclosure. Some students perceived the enclosure mechanism and decoration as creative components. Another interpretation was a decorated package with a creative name that also had individualized positions for each crayon and pad.

And lastly, the final group of participants incorporated elements of function, implicit problem solving, and elegance into their design. In one example, an individual prioritized function by creating a snug, separated fit (implicit problem solving) for both crayons and the pad in a simple (elegance) container while another focused on an everyday object (implicit problem solving to add originality) to hold the crayons and pad in one pouch (function) in a neatly constructed way.

Conceptions of creativity informed how participants approached the design requirements of a domain specific task; the creation of a package to hold six crayons and a sticky notepad in a functionally creative way. Group one indicated conceptions of creative design more remote from those of design practitioners than those of the other groups. Group two and three contained conceptions that were similar to practitioners, however some included artistic creativity which is not essential to engineering design. Group three indicated a disconnect between artistic and engineering creativity. And the last group, group four, aligned more closely with repertoires of engineering practice.

RQ 2: What creative approaches and elements emerged in product design?

Figure 3.2 illustrates the creative approaches considered by participants during product design. In most cases participants emphasized functionality in comparison to originality, however, for some the goal was to balance the two. Furthermore, the majority of students utilized some form of ideation. This was expressed through the generation of multiple *mental* ideas prior to sketching, as elaborations on initial ideas, and by modifications to prototypes and/or sketches.

When asked how packages were designed to be creative, participants generally responded by saying it was the unique shape or set of features that made the package appear as other well-known everyday items. Participants saw originality as the departure from the cube-like shape as shown in the example provided to represent an unoriginal package (see Appendix A). Jessica's statement about how her package was creative encompassed both ideas when she said, "Um, I would say the shape is creative. Um, the angle combinations, I guess. Maybe the two different pockets. I'm not sure that most boxes would have something like that" (36 – 38). Her words insinuated the notion that originality was an idea few others would think of and that distinctive shape provided a mode to incorporate everyday objects (pockets) as storage to create a novel design. The transposition of pockets from items such as clothes, luggage, backpacks, etc., to a package was unique. Simple everyday items were transferred from one context to another.

Figure 3.3 displays the outcome of the design process as interpreted by first-year engineering student participants. Observing the products of design reveal another perspective on how the participants conceptualize an understanding of originality and functionality. The center elements: *novel components*, *shape*, and *everyday items*, exemplify the fundamental ways in which participants pursued creativity (originality) in the design of a package. Other participants envisioned combining multiple elements to create an original package. The left and right columns convey participant conceptions of adjoining the center elements as indicated. The left unites novel component(s) with everyday objects. Novel component(s) and shape, as well as shape and everyday objects, are depicted on the right.

Elements are accompanied by sample designs to represent the characterization of each group in Figure 3.3. The *novel component* element adds a feature to distinguish it from a mere cube-like box. The examples shown from left to right comprise a fancy fastener, multiple slit and flap features to maintain form, and origami. The element *shape* refers to designs that chose to focus on “other shapes as different from cube”. Representations depicted of *shape* are: pyramid, hex prism, and disk. *Everyday objects*, the last fundamental element, is self-explanatory. These exemplify common objects seen in everyday life. This group maintained objects that were streamlined, boxy, and angled in form. No intricate shapes were included in this group. A crayon box, a crayon, and set of drawers illustrate representative examples of *everyday objects*.

Novel components and shape shows an elongated narrow rectangle with a separation component and specific holders for each crayon, a hexagon-like disk with a flap and band feature, and a shape created by folded paper to provide rigidity for an enclosure feature. A purse, rocket ship, and envelope provide examples of *shape and everyday objects*. A planner and salt container, both with unique fasteners, and a Lazy Susan placed upon detachable storage each represent examples of *novel component(s) and everyday objects*.

The packages were assigned to groups based on what participants said about what inspired them and what they were designed to look like. For example, the third picture under *novel components* and *shape* could appear, to someone, like a McDonald's pie container. This object was not placed in the *novel component* and *everyday object* category because the designer did not intend for it to look like a specific object.

Participants arrived at a diverse set of designs through different design processes. The last research question examines the types of processes students utilized to design packages.

RQ3: How are components of the design process employed during product design?

Thirteen different design processes were utilized by the 155 participants in this study. Nine of those processes are presented here. The remaining four processes were closely related to other design paths similar to those defined in Figure 3.4.

The first column, on Figure 3.4, from top to bottom contains the words: visual memory, visual stimuli, and improvisation. Visual memory relates to thinking about, or internally visualizing a purposeful design. Those who were inspired by objects within visual proximity around one's physical body initiated the design process with visual stimuli. Improvisation, generally, described individuals who designed without a plan or inspiration, at least that is how they conveyed their process. This was ambiguous and possibly the result of insight problem solving rather than creative problem solving. Insight problem solving comes in many forms, but is expressed as an intuitive response that spontaneously emerges without following a deliberate process (Wallace, 1991).

The white arrows in Figure 3.4 that end at construct indicated the most common design process path utilized by participants. The simple process included thinking of one or more ideas and quickly narrowing it down to just one solution followed by one or more sketches of the design. When participants were happy with their sketch, they constructed the package and turned it in. The second most common path, as identified by the dotted arrows transposed the last two steps of the most popular path. Here, students constructed the package first and sketched it later. Participants who carried out the design process in this way said they preferred to have an object to look at when they sketched.

The addition of a modification step before construction (visual memory → sketch → modify → construct) and after construction (visual memory → construct → modify → construct) exemplify two other models. Modifications, as reported by participants, either enabled the package to conform to the participant's original plan (due to such things as measurement errors) or were needed as the result of another ideation process because of the dissatisfaction with the present design. One process included two modification steps (visual memory → sketch → modify → construct → modify). Participants revised their designs in some way after their initial sketch and after construction of the package.

Another design path (visual memory → construct → modify → construct → modify) was reminiscent of a trial-and-error approach. Participants created a prototype from memory, tweaked it, fixed it or recreated it, and then tweaked it again after reconstruction. This group did not report using any sketching at all. The last visual memory route started with package construction followed by modification. Sometimes these modifications caused the participant to reconstruct. It was only after the participant felt satisfied with the product that they drew a sketch, in this case.

A few participants depended on visual stimuli for inspiration. For instance, James came up with a drawer storage design by looking around his dorm room. There in front of him was a bureau. Individuals with this perspective sketched the package first and then constructed it. It is important to note that in this case the participant was able to sketch the object in plain view because the visual stimulus was in front of them.

Discussion

Although some participants had conceptions inconsistent with the field of design about what it means to be creative in one area (e.g. design elements), most participants were able to conceptualize expectations in another area (e.g. the design process). For example, those who decorated a cube or rectangular-shaped object did come up with multiple designs or ideas before committing to just one. Over half of participants reported at least two design ideas, but most ruled out designs, in favor of another, before sketching or constructing. Factors responsible for early design decisions were time, complicatedness, and resources. Participants felt limited by the amount of cardstock given and they did not want to waste material trying to construct prototypes. This is reinforced by previous research showing that McCoy and Evans (2002) found that lack of time and resources were tangible obstacles to creativity.

For those students (13 out of 155) who had only one design idea explained there was no need to come up with more ideas if the initial idea worked. These participants did not elaborate on or modify the single design. Design fixation has been reported (Atman et al., 1999; Shah et al., 2012) to plague designers. In particular, realistic photographic images, used as inspirational elements, caused design fixation (Cardoso & Badke-Schaub, 2011a). Participants who said their design process began with visual stimuli did not modify or elaborate on the design at all. Those with more design ideas to choose from had more creative designs with composite features (see Figure 3.3; first picture under *Novel Components* and *Everyday Objects*).

Inspiration for the design of final products most closely connected with near associations. Participants talked about toys they had as a child, desk organizers, Happy Meals, purses, and Chinese take-out boxes. These are all generally recognizable storage items. Cardoso and Badke-Schaub (2011a) would describe these as between-domain analogies because the aforementioned objects are not strictly designated as design domain ideas. No one contributed what would be considered a far association: a connection between two disparate objects like a sandwich and Punky Brewster. Participants mostly utilized concrete objects as inspiration. Only one person considered emotions, personality, i.e. abstract notions as inspiration. She stated the inspiration for her design came from children and fun.

Originality or problem solving, supported most of the participants' overall goal—

functionality. A short list of factors imposed by designers was generated to illustrate what was important to individual participants in the construction of a package. Elements of problem finding were uncovered by findings that evolved from implicit problem solving. Participants who engaged in implicit problem solving believed the objects (crayons and pad) should be separated to prevent the crayons from soiling the package. In addition, participants wanted the components to fit within a simply designed package that focused on accessibility. Simple meant easily constructed and accessibility referred to trouble-free usability. Simplicity was valued over complexity because participants felt complex structures and features contradicted the goal of functionality.

Participants who focused on a separation component and fit, created a wide range of finished products. Some elected to create a package with two completely separate compartments that snugly held all the components discretely while others concentrated on a loose design that allowed the crayons and/or pad to move freely within the package.

Participants considered who might use the package. The most common responses were: children, the general public, and themselves. Designing for a specific customer affected how participants went about creating original elements to complement functionality. Individuals designing for children discussed adding fun aspects to draw children's attention. The middle picture under the heading *Everyday Object* of Figure 3.3 illustrates a package designed for a child. It replicated a crayon- just like the components it was meant to hold.

Summary

Participants had varied conceptions of creativity in engineering. The spectrum of views spanned from the dichotomy between art and science to creativity as problem solving. Other participants stated creativity was apparent everywhere and in everything.

All participants engaged in the ideation process and generated multiple ideas. Participant designs either emphasized function over originality, or balanced function and originality. No one favored originality over functionality. This was supported by what participants said and by what was exhibited in final product constructions. Additionally, the majority of participants viewed the design process as a linear procedure: idea generation, sketching, and construction.

Limitations

A limitation of this study was the small convenience sample of interview participants (six), relative to the 155 total participant sample. Course credit was earned for participation in the project, not participation in the study; however, most students did not participant in the project. Therefore, the sample may be skewed in favor of those who needed credit to improve grades in the course and those who are consistently motivated to complete all assignments. Hence, the project-completion participant group may not be representative of the entire class. However, the interview served as an additional source of the same data collected by other data sources (open-ended questionnaire, drawings, and participant-generated products).

Conclusions, Implications, and Further Studies

First-year engineering students had varied conceptions about what constituted creative elements in design and creativity in the design process. Confusion over the difference between creativity in art and engineering was evident based on what participants said, by final products, and by the design process utilized by participants. Creative distinctions between art and engineering need to be explicitly discussed with students. Although, *creativity as problem solving* is obvious to the ECoP, newcomers may have difficulty with the word "creativity" and its alternate meanings.

Participants, in general, were knowledgeable about generating multiple ideas and selecting the best option(s) based on assumptions, criteria, and constraints. They participated in the practice of brainstorming— a divergent thinking process. As part of the CPS model, problem finding was evident as participants found multiple implicit sub-problems within the overarching broad problem of functionality and creativity. However, all of these important elements occurred on a small scale and participants were quick to choose (evaluate) options. Evaluation— a convergent thinking process, is typically overemphasized in engineering (Daly et al., 2014).

Instructional strategies such as Problem Based Learning (PBL) or Design Based Learning (DBL) with a focus on ill-defined problems could provide learners with experiences that replicate authentic engineering practice (Dym et al., 2005; Yusof et al, 2016) if targeted at an appropriate content level. Participation in authentic engineering tasks permit the development of practice-linked identities (Nasir & Cooks, 2009) and cultivate refinement of repertoires of practice (Rogoff et al., 2007).

In particular, actively engaging with creative components of design problem solving emphasizes, and makes explicit, the purpose of utilization of both divergent and convergent thinking skills for the purpose of creating functional and original products, processes, and services. An introduction to CPS could begin at the K-12 level.

Kurtzberg and Kurtzberg (1993) found that middle school students came close to arriving at the same solutions as the former Soviet Union did just after its collapse. Students, as part of the Future Problem Solving Program (FPSP), were able to determine the sub-problems by category (economic, social, political, etc.) and work through possible solutions. Practice with the process, although rooted in different subject matter content, would expand students' repertoire of practices.

Determining whether students can select and transfer a practice or idea (from one domain to another) as appropriate for design tasks or ideas is an interesting question. Students may have ideas, and know and understand how to complete required tasks, but be unaware that these ideas or tasks can be combined to form novel products. The associative theory of creativity suggests the ability to fuse two or more distinct ideas sharing a common theme produces original ideas, or in this case, original product ideas. Individual's need to practice forming associations in order to benefit from the advantages that arise from the associative theory of creativity. Participants, generally, exhibited associations between storage devices across domains. Other participants utilized elements from different domains to create a new object.

Important questions for future studies include, what do K-12 students know about engineering? How can K-12 students' implicit theories about the practice of engineering be characterized? In what ways are they different from explicit theories? It's plausible that K-12 students may have similar conceptions as the college level students in this study; however, the general K-12 population does not have the same level of interest as individuals' who have chosen to study engineering. The Next Generation Science Standards (NGSS) for science education require science instruction to include the practices of engineering (NGSS, 2013). Blending science and engineering can be confusing for students and teachers. How do teachers and students differentiate the two? The nature of science and nature of engineering share common features, but also focus on different aspects. The nature of science is about discovering what already exists and the nature of engineering is about invention— developing new products that have never existed before.

Constructing lessons that both differentiate and demonstrate coherence between science and engineering is an overwhelming task. Design and Discovery (Intel Corporation) and The Infinity Project (Southern Methodist University) offer K-12 engineering education curricula available to teachers (NAE & NRC, 2009).

The importance of divergence of ideas in engineering counters science pedagogical techniques such as conceptual change which focus on the convergence of an accepted idea or concept. Alternatively, implementation of design challenges in classrooms with a focus on one scientific principle does not illustrate engineering principles. Engineering combines multiple concepts from different domains to create something new.

Additional possible research questions include, what are instructors' implicit theories about engineering design? Postsecondary instructors teaching introductory design and engineering science courses may not have a background in engineering as science teachers generally do not. Instructor implicit theories directly affect student views about engineering because instructors determine what is taught and how it is taught. Instructor views that more closely align with explicit theories of engineering design have the capacity to develop transformative experiences for students.

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COMPONENTS OF FUNCTIONAL CREATIVITY

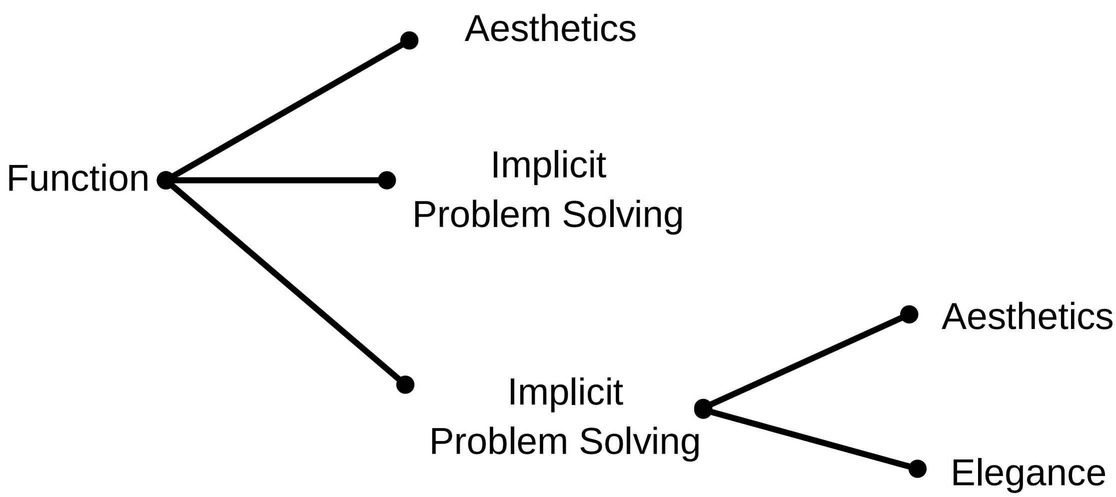

Figure 3.1. Representation of conceptions of functional creativity.

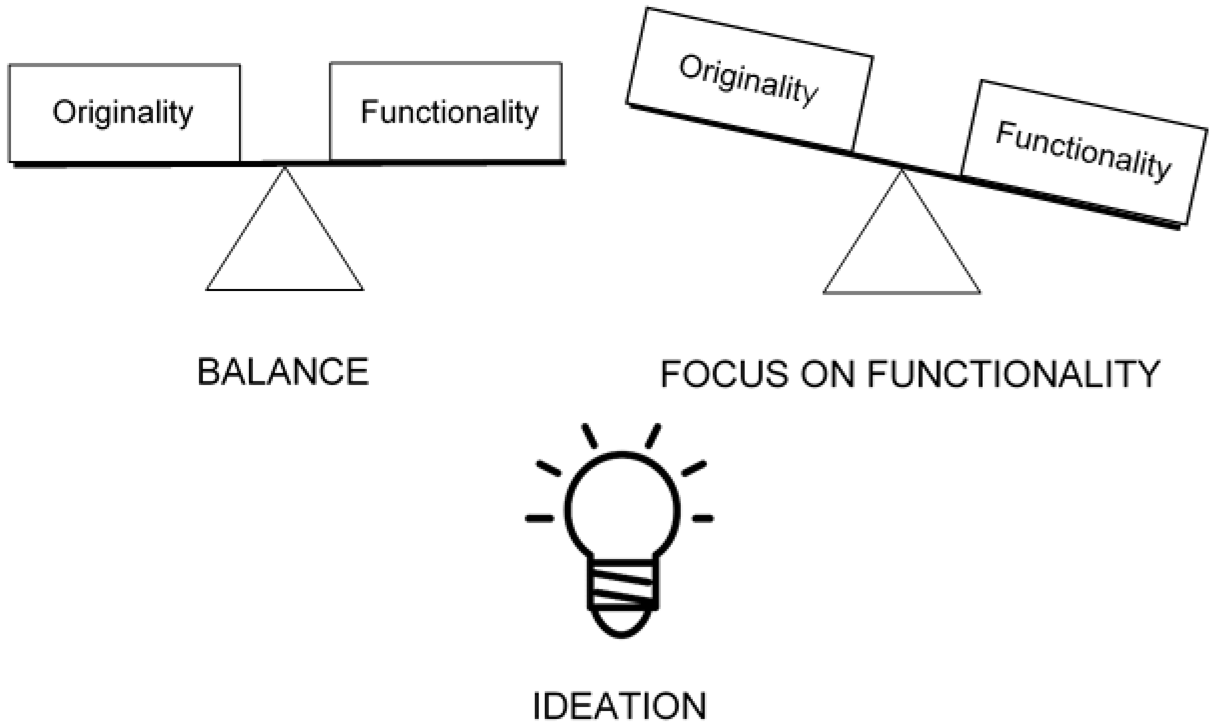

Figure 3.2. First-year engineering students' creative approaches to product design.

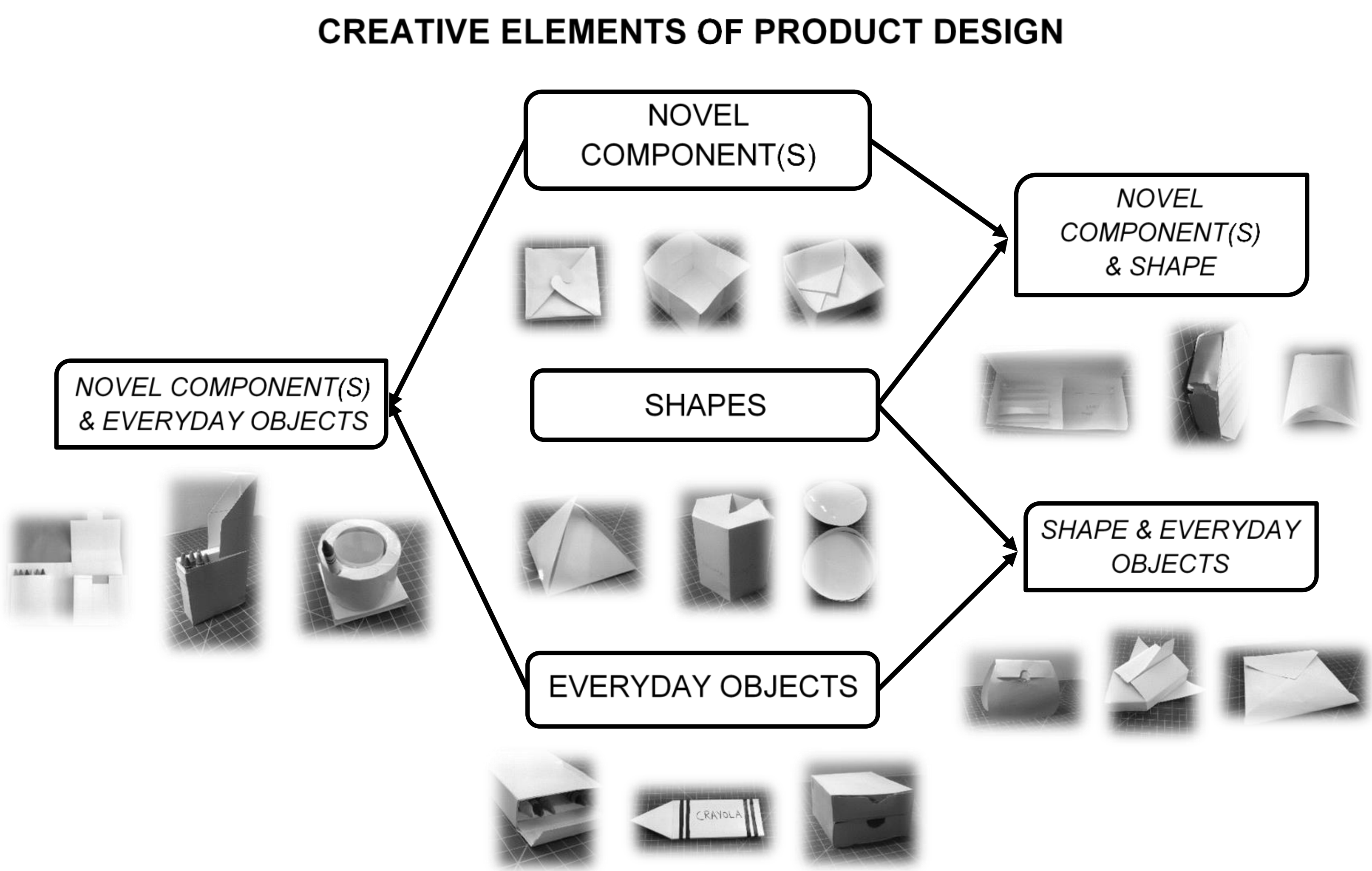

Figure 3.3. Examples of products to illustrate how students conceptualized functional creativity.

DESIGN PROCESSES UTILIZED BY PARTICIPANTS

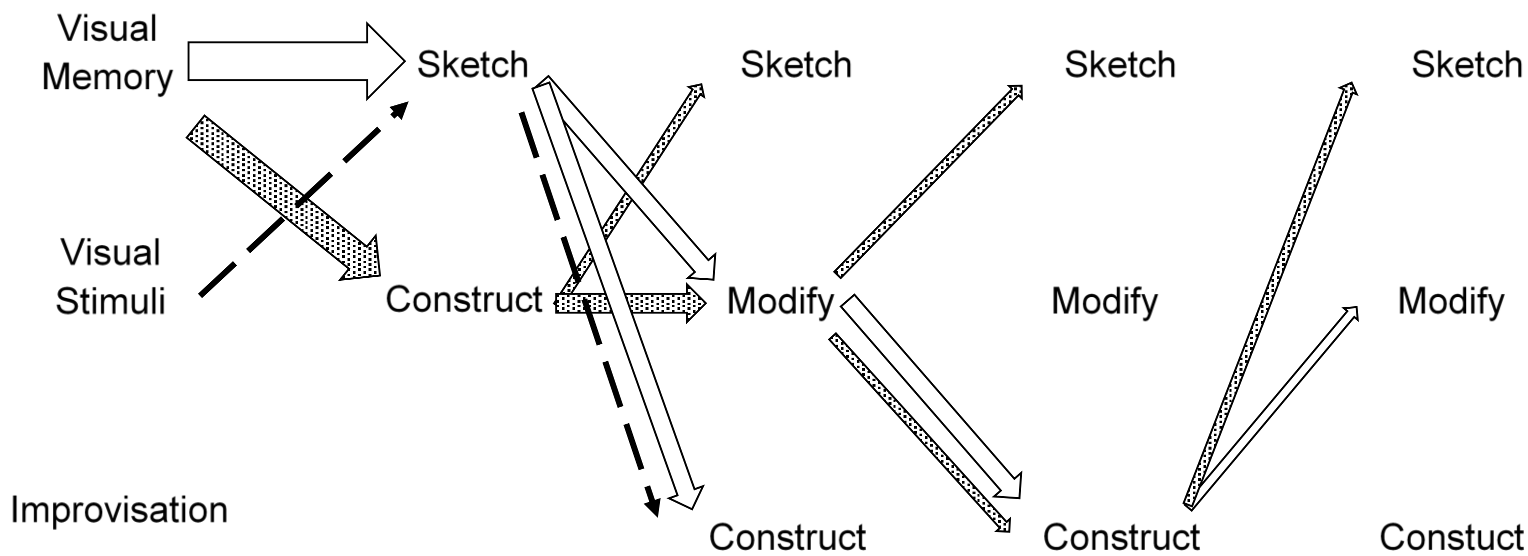

Figure 3.4. Step-by-step actions conveyed by participants from idea through construction.

CHAPTER 4

CREATIVITY IN DESIGN: WHAT'S SPATIAL SKILL GOT TO DO WITH IT?[3]

[3] Murray, J. K. To be submitted to the *Journal of Engineering Education*.

Abstract

Spatial and creative skills developed through interactions with the social world manifest in different ways as a result of experience, personal values, and interest. This research study examined the relationship between spatial skills and creativity of 122 first-year engineering students at a large southeastern university. The mixed methods approach employed a concurrent nested research design that embedded quantitative data into a predominately qualitative study. The purposes of complementarity and initiation supported the utilization of a mixed methods approach to collect data across multiple facets of the phenomenon. Findings revealed males scored higher on creativity and spatial skill assessments than females, although not significantly higher. However, females did not score at the highest levels of creativity, as did males. Those at the highest creative level (males) indicated a strong significant correlation among spatial visualization assessments. Creative product rank scores (CPRS), from one (lowest) to five (highest) were also compared to spatial skill across gender. CPRSs among males was weakly (r_S = .25, p = .019) and moderately (r_S = .33, p = .001) significant to paper folding (PF) and surface development (SD), respectively. There were no significant correlations between female CPRS and spatial skill level. In addition, a few trends emerged from the data. Participants earning high CPRSs tended to have more ideas and frequently used AutoCAD™ in design. Participants with high and low CPRSs were more likely to stay with one design throughout the design process. And finally, all with a CPRS of five did not modify their designs at any time throughout the design process. Modifications were most prevalent in CPRSs four, two, and one; however, modifications among low scorers were due to errors (measurement, inappropriate cutting, etc.)

Introduction

Creativity in innovation propels products to new dimensions of achievement. Many products begin as internal visualizations that are eventually realized through external representation and successive iterations guided by recursive design cycles to advance initial design conceptions. Technical innovation has always been important to the U.S. and the government has heavily invested in scientific education throughout history.

Recently, the U.S. prioritized STEM education with the founding of Educate to Innovate (House, W., 2009). The goals of the initiative were: 1) the creation of a coalition for collaboration between government, industry, non-profits, and philanthropic organizations with the purpose of enhancing STEM knowledge education; 2) training STEM teachers; and 3) broadening participation in STEM fields.

Soon to follow, in a memorandum to the U.S., was a plea from the chairman of the National Science Board (NSB) urging the U.S. to heed "recommendations on how to support the identification and development of talented young men and women who have the potential to become our Country's next generation of science, technology, engineering, and mathematics (STEM) innovators" (NSF, 2010, p. v). "STEM 'innovators' are defined as those individuals who have developed the expertise to become leading STEM professionals and perhaps the creators of significant breakthroughs or advances in scientific and technological understanding" (NSF, 2010, p. vii). The National Science Foundation (NSF) emphasized scientific and technological innovation whereby innovation referred to the use of knowledge, skills, creativity, and foresight to advance and expand upon discovery and construct new knowledge.

Then came the proposed framework for K-12 science education standards with a focus on disciplinary core ideas, cross-cutting concepts, and science and engineering practices (NRC, 2012). The framework was released to the public for inspection and the development committee accepted feedback before a revised framework was established. Today the Next Generation Science Standards (NGSS, 2013) represent an accepted version, by consensus of scientists, cognitive scientists, science education researchers and policy experts, of the content that should be taught in K-12 science classrooms.

It is notable that a committee for engineering standards was present during the development of the K-12 science education standards. Emphasis was placed on identifying problems and designing solutions within the science and engineering practices of the NGSS. Ironically, creativity was not mentioned as part of the science and engineering practices or associated with any other component of the standards. Spatial skills were recognized as significant to the disciplinary core ideas of earth's systems.

Innovation does not occur without creativity (Cropley, Kaufmann, & Cropley, 2011) as suggested by the NSF (2010) and House (2009), but it is missing from the NGSS (2013). Inconsistency among national documents advocating STEM education makes it difficult to discern a proper way to prepare students for future learning. Educators may select facets of STEM they want to or are told to focus on, and initial formal introduction to design will vary. Implicit and explicit views of design affect conceptions of repertoires of design practice.

Experts, those who have engaged with a practice for years and have attained a status of full participant in a community of practice (Lave & Wenger, 1991), have experienced different types of memberships in the community. Exposure to multiple levels of participation offers experts insight to an evolving perspective of the practice. In essence experts gain a deeper understanding of how all the parts fit together as a whole.

In some instances, individuals attain eminent creativity. Einstein, Faraday, Maxwell, Tesla, and Galileo have attributed scientific contributions to an ability to visualize what is not readily visible (Kozhevnikov, Motes, & Hegarty, 2007; Kell & Lubinski, 2013). Gilbert (2008) explains that the ability to transform an internal visualization into an external representation constitutes creativity. In addition, if the external representation is in the form of a schematic it is even more creative because the drawing is a metaphor for an abstract concept (Ramadas, 2009).

As peripheral legitimate participants (students), at the beginning of a journey through a new community of practice, how do students' spatial and creative skills align with the design community of practice? As newcomers to the practice, do students' spatial and creative skills support one another?

Background

This investigation explored the intersection of spatial skill and creativity within the domain of design utilizing the object-spatial-verbal theoretical model and theories of creativity. The assumption was that an ability to manipulate objects in one's mind facilitates the creative design process in the following ways by: visualizing existing designs, visualizing modifications, and visualizing novel solutions.

Visualization, as suggested by the object-spatial-verbal theoretical model has two components: spatial system and object system (Kozhevnikov, Kosslyn, & Shephard, 2005; Kozhevnikov, Hegarty, & Mayer, 2002). Spatial system visualization is the ability to imagine and represent spatial relations between object components, an object's location in space, and their movements. Object system visualization is the ability to imagine and represent the detailed visual appearance of an object via shape, size, color, brightness, etc. The spatial system and object system are relevant to STEM and visual art fields, respectively.

Spatial System

The focus of this study was on engineering and thus the spatial system was of importance rather than the object system. The spatial system is subdivided into four parts: object manipulation, perspective taking, spatial perception, and disembedding (Uttal et al., 2013).

Perspective taking, or the space of environments (Hegarty, Crookes, Dara-Abrams, & Shipley, 2010), signifies shifting visual perspectives of a stationary object (Gagnon et al., 2013). The skill is split into two perspectives: survey and route. The survey perspective views the world from an out-of-body perspective. Associated with map reading the survey perspective utilizes schematic representations and the North-South-East-West coordinate system to denote direction. The route perspective applies an egocentric view. Individuals employ the memory of previous experiences to navigate space from an in-the-body perspective.

Spatial perception involves the skill to determine how components of an object are oriented in a new position dependent upon external accelerations (Tversky, 2005).

For example, changing the orientation of a car or glass of water from its upright position will change the orientation of a plum line attached to a car or the water in the glass (Linn & Petersen, 1985). Disembedding as exemplified by hidden figures tests is the skill of locating objects through distraction. This skill may be useful when surgeons look for abnormalities such as cancer in visual images of the body.

Object manipulation encompasses mental rotations and spatial visualization (Kozhevnikov & Hegarty, 2001). A single rotation defines spatial relations. Rotating a square clockwise 90 degrees exemplifies a 2D spatial relation while rotating a cube around the x-, y-, or z-axis is a more complicated 3D rotation. Spatial visualizations often involve multiple manipulations. This study focuses on object manipulation skills because these skills have been most associated with scientific/engineering visual skill.

Creativity

Creativity is an essential component of innovation. To clarify, innovation denotes the transformation of creative ideas into products (West et al., 2012). The development of novel and useful innovative products begins with creativity. Novel ideas that serve utilitarian purposes embodies the essence of creativity (Runco, 2004). In both cases (creativity and innovation), creative thinking is necessary and includes two modes: associative (generative) mode and analytical (evaluative) mode. Creativity involves *generating* novel ideas that draw upon associations from remote domains that combine because of a shared feature, and this is followed by an *evaluation* of new ideas for their usefulness. Creativity, as the sum of both generative and evaluative modes, propels new perspectives, products, processes, etc., forward.

Generative Mode

Idea generation, or ideation, are other names for the generative mode of creative thinking which is dominated by divergent thinking. Merging two or more ideas with the purpose of creating new and original ideas characterize this mode. This concept originated with the associative theory of creativity (Mednick, 1962). The associative theory of creativity states that novel ideas depend on remoteness of ideas in relation to other ideas while still maintaining a common thread. The farther the ideas span from one another the more original the new idea becomes. Higher levels of creativity are consistent with more remote connections formed between ideas.

Mednick (1962) labeled the level of association between ideas in a hierarchical system. Ideas that begin as original and transform into variants of that idea are called steep-associative hierarchies. Near associations are also part of this hierarchy. Flat- or shallow-associative hierarchies imply a constant stream of remote associations that do not become narrower with each new combination. Mednick (1962) believed that creative individuals used flat-associative hierarchies because they had attained a wide knowledge base and ability to retrieve elements from memory.

Evaluative Mode

The evaluative mode determines whether ideas, solutions, processes, etc. are creative (Runco & Acar, 2010). When innovation is the goal it is more appropriate to suggest the evaluative mode is the process of selecting and/or refining ideas, solutions, processes, etc. in order to establish the best alternative to develop (Sowden, Pringle, & Gabora, 2015).

Convergent thinking dominates the evaluative mode, and is the process of selecting ideas, concepts, processes etc., based on a set of criteria and constraints required in a particular context within engineering.

Domain Generality and Specificity

Engineering is principally about improving upon existing products, but sometimes new products are developed from scratch. This is different from art—a distinct domain. Artists do not improve upon famous works of art such as Leonardo DaVinci's Mona Lisa, they tend to generate original art.

The creative research community, however, has not yet settled on whether or not creativity is domain-general or domain-specific (Baer, 1998). People like Leonardo DaVinci, with creative abilities in art, science, math and engineering, provide support for the possibility of creative domain-generality. Multiple expressed creative traits across domains is atypical. Others believe creativity is domain-specific because prior knowledge and experience underpin specific creative attributes.

In either case, creativity depends on combining remote ideas or concepts to form novel ideas according to the associative theory of creativity. There is no advantage to pursing a domain-general approach to creativity (Baer, 1998). If solid evidence emerges for either domain-specificity or domain-generality, then domain-specific skills can transfer to other fields, but not vice versa.

Creativity and Visualization

Besides the link between eminent creativity in science and the spatial nature of thought and metaphors in external representation, researchers have tried to connect creativity and visualization among highly creative individuals— not eminence in science, engineering, and art.

As previously noted, Kozhevnikov, Kosslyn, and Shephard (2005) determined that two visualization pathways exist: object visualization and spatial visualization. Individuals with stronger object visualization skills preferred to generate concrete images of objects. Object visualizers could remember details about objects and recall them later. Stronger spatial skills enable schematic representations of phenomenon and an ability to rotate objects internally. Further study found scientists and engineers excelled at spatial visualization while visual artists dominated object visualization in comparison to one another (Blazhenkova & Kozhevnikov, 2009). To solidify these findings Kozhevnikov et al. (2013) provided a wide variety of spatial and creative assessments to a variety of college students with different majors. Again, artistic creativity was linked to object visualization and science/engineering creativity was connected to spatial visualization. Each was separate from verbal creativity— skills related to communication.

Kell et al. (2013), compared verbal, mathematical, and spatial scores with STEM publishers and patent holders. They found that patent holders had high spatial scores and more average verbal and math scores. STEM publishers, however, achieved high scores on both spatial and verbal scales. When high scoring math and verbal individuals were investigated, only 1% of high scoring spatial individuals emerged from the group. Therefore, talent had gone unnoticed due to an emphasis on verbal and mathematical skill.

Allen (2010) attempted to find a connection between creativity and visualization in second year interior design students. The cube comparison and surface development tests were used to assess two dimensions of spatial visualization. Both of these tests were used in Murray's Dissertation Chapter 2 (2016) to assess spatial skill level. Expert judges rated interior design projects in relation to one another based on three criteria. Allen's analysis (Spearman's rank correlation) concluded no significant relationship existed between visualization and creativity. In addition, the correlation was very weak.

Methods

Pragmatism of the middle, based on ideas set forth by Charles Sanders Peirce, William James, and John Dewey guided this study. Fundamental to pragmatism is the blending of realism with constructivism for the purpose of uniformity among theory and practice (Greene & Hall, 2010). Dewey's transactional constructivism describes knowledge as a human construction rooted in an external reality (Biesta & Burbles, 2003). The combination of positivism and constructivism enables an enhanced description of the phenomenon under investigation (Johnson & Onwuegbuzie, 2004; Johnson, Onwuegbuzie, Turner, 2007). The provisional nature of knowledge, meaning, and truth leads to tentative findings.

Central to the pragmatist tradition is utilization of any method for the purpose of answering the research questions. The overarching research question is: *In what ways does first-year engineering students' spatial skill relate to creativity in design?* Three sub-research questions divided and addressed attributes of the overarching question. The three sub-questions were:

1. What is the scope of students' spatial skill?
2. How is student creativity expressed in product design and in the design process?
3. To what extend does spatial skill play a role in creative design?

The findings from the first two independent questions contribute to the third predetermined mixed methods sub-research question (Plano-Clark & Badice, 2010). These questions inform the research design as described in the next section.

Research Design

A concurrent nested mixed methods research design type (Creswell, Plano Clark, Gutmann, & Hanson, 2003) was selected for this investigation to embed quantitative data within a collection of qualitative methods. Quantitative data were gathered to characterize participant spatial skill across spatial skill assessments. In addition, participants generated physical products, drawings, written explanations of how products were created, and answered an open-ended questionnaire. These data sources qualitatively captured creative and spatial aspects of the design process and elements of product designs.

Complementarity: exploration into multiple facets of the same phenomenon-design creativity (Greene, 2007), was key to the study. Physical products revealed creative elements integrated into design while written explanations of product creation exposed creative components of the design process. This also exemplified initiation (Greene, 2007) because each facet was examined with a different method. Similarly, spatial data was assessed quantitatively and qualitatively, respectively, with a context-free assessment and through participant drawn product designs.

Several multiple choice assessments (card rotation [CR], cube comparison [CC], form board [FB], paper folding [PF], and surface development [SD]) were used to measure 433 participants' spatial skill level (Ekstrom, French, & Harman, 1976). The Revised Purdue Spatial Visualization Tests: Visualization of Rotations (Revised PSVT: R) (Yoon, 2011) test was also selected because it is most often utilized in colleges of engineering to assess spatial skill.

Furthermore, a design task (see Appendix A) was given to participants directing them to create a package with two 12 x 12 inch sheets of cardstock. The challenge was to design a functional and creative package that would hold six crayons and one sticky notepad. Participants worked on the project outside of class for about a week. They worked individually, but could consult resources to help them plan and construct their designs. In addition, they provided written descriptions about how packages were designed. Specific questions included inquiry into the process, number of ideas, and inspirations participants considered. Two dimensional (2D) and three dimensional (3D) drawings of products were also incorporated into the data set.

Study Context

Participants were enrolled in an AutoCAD™ course—a first course in engineering, required of all engineering majors at a large southeastern university. Data was collected over three consecutive semesters. All students received credit for participating in each part of the study; however, only those who permitted consent were added to the study. A total of 433 students authorized use of their spatial assessment data and 155 students approved use of their product designs. In all, 122 sets of spatial-creative data were available for analysis.

Data Analysis

Scores for all individuals' spatial assessments were added to JMP® for comparison among and between assessments and individuals. A nonparametric technique: Spearman's rank correlation test, was used to evaluate relationships between spatial assessments because the data was not normally distributed. A Mann-Whitney U test assessed differences between male and female scores on each spatial assessment. Construct validity for the assessments was previously reported (Ekstrom et al., 1976); however, Cronbach alphas for each assessment were calculated for this study and were found to exceed .8—high enough to be considered reliable.

All data related to the design and construction of the package were initially qualitatively evaluated. Pictures were taken of packages, written documents scanned to PDF files, and each were uploaded as separate documents (per participant) into Atlas.ti (Scientific Software Development, 2011). Applied thematic analysis (ATA) initially ensued to generate inductive themes. "[T]he greatest strength of ATA is its pragmatic focus on using what-ever tools might be appropriate to get the analytic job done in a transparent, efficient, and ethical manner" (Guest, MacQueen, & Namey, 2011, p. 18). Codes were developed for the purpose of supporting the themes with evidence. Thematic analysis was first used to find emerging themes followed by the application of a priori codes developed from the conceptual framework that guided the study.

The package products were then divided into five categories according to relative creativeness in comparison to other student generated product designs. The first author and three colleagues ranked packages based on Cropley and Cropley's (2005) four dimensions of their theoretical construct—functional creativity. Raters evaluated packages based on separate dimensions of relevance and effectiveness (functionality), novelty (originality) and elegance. In addition, products were compared holistically with one another (O'Quinn & Besemer, 1999) by rank ordering products against one another.

Ratings were averaged, but were consistent across all dimensions with the exception of one design. Therefore, interrater reliability was 98%. This approach was chosen to align with Amabile's (1982) Consensual Assessment Technique (CAT) and the Creative Solution Diagnosis Scale (Cropley & Kaufmann, 2012). CAT assumes that an appropriate group of raters can decipher levels of creativity people can agree upon. Experts are not needed in this case, just raters that are familiar with the product being assessed (Cropley & Kaufmann, 2011). The purpose of quantifying product creativity was to directly compare creativity and spatial skill level of participants.

Qualitative and quantitative data were merged at the analysis phase. Themes supported statistical relationships and vice versa to generate trends or statistical correlations in the data. Sub-research question one was answered by purely statistical methods. The sample acquired in Murray's Dissertation Chapter 2 (2016) was qualitatively compared to the subsample of this study. The second sub-research question focused on creativity in product design in comparison to creativity in the design process. Lastly, the third sub-research question joined data from the previous research questions to consider relationships between spatial and creative data.

Next, the finding present what was found after an analysis was conducted to answer the overarching research question: In what ways does first-year engineering students' spatial skill relate to creative design?

Findings

Spatial Skill

Spatial skill, as reflected in the results of a series of object manipulation assessments, of participants was wide-ranging. Figure 4.1 and Figure 4.2 illustrate the characteristics of participants' mental rotation and spatial visualization skill level, respectively. The histograms show the score, in percent, on the y-axis. Comparisons of gender across all assessments rendered by a Mann-Whitney U test yielded no significant differences in scores except for the Revised PSVT: R. The mean ranks of the Revised PSVT: R were statistically significant at the $p = .0047$ level. An effect size was found to be $d = 0.53$ (Cohen's *d*) and consistent with what Maeda and Yoon (2013) reported in a meta-analysis of previously published data of PSVT: R relevant studies. See Murray Dissertation Chapter 2 (2016) for more specific results of the object manipulation assessments.

A sub-sample of the original sample produced a creative product in addition to completing the spatial assessments. Table 4.1 presents the results of a Spearman's rank correlation test applied to the sub-sample. Furthermore, a Mann-Whitney U test was performed to identify any differences between males and females. The test revealed the sub-sample differed in PF skill. According to an estimation generated by a chi squared distribution ($\chi^2 = 4.49$) the significance level was $p = .034$ with males scoring higher than females.

Creative Design and the Design Process

Creative Rank of Product Designs

Example product designs assigned to creative rank groups are depicted in Figure 4.3. A creative product rank score (CPRS) of five had overall high scores on functionality, originality, and elegance. Products assigned to creative product rank group (CPRG) one were placed there because they were not original or elegant. In some cases, the products were not functional. CPRG three had average products, in comparison to other classmate designs. This group generally included functional products with subtle original features perhaps enhanced by elegance. Products positioned in CPRG four varied from functional products with unique features that were not so elegant to functional products of above average elegance and mild originality. CPRG two products were functional with a bit of originality, but the elegance varied.

Figure 4.4 displays the distribution of CPRS of participant generated designs. The mean scores were 2.37 and 2.39 for males and females, respectively. Notice that those awarded a score of five were only earned by males, but a larger percentage of products generated by males earned a score of one. A Mann-Whitney U test indicated, according to a chi square approximation, that the two samples were not significantly different (p = .63) from one another.

The creative rankings of participant product designs were often associated with creative components of the design process. These trends are outlined below.

Trends Between Creative Product Rank and Elements of the Design Process

Four creative trends emerged from the data between the design process and creative product rankings. First, participants with higher CPRSs were more likely to use

AutoCAD™ to generate drawings during the design process. These 2D and/or 3D computer-modeled drawings were created either before or after construction of the product. Individuals with lower CPRSs tended to sketch ideas by hand, only. In addition, designers with multiple ideas generally scored higher on product creativity in comparison to those who had one idea and progressed through the design process with few or no modifications.

The last two trends are denoted in Table 4.2 by percentage of participants engaged in the modification of designs or the development of only one design. None of the designers with products in CPRG five modified their design. Those with a CPRS of two or four had similar percentages of group members modify the design at some point throughout the design process. The difference existed in why particular designers modified designs. Individuals in creative product rank group four modified designs to enhance, add, or remove features to improve the overall design. For example, containers designed to hold hot or cold substances benefit from the addition of a handle or strap to minimize the transfer of heat across boundaries that could cause bodily injury. Modifications made by participants in CPRG two were the result of modifications based on feature improvements and measurement error. For instance, some participants in this group had to modify designs because the notepad or crayons would not initially fit, or the cardstock was cut based on incorrect measurements. Individuals in CPRG one had similar issues as those in CPRG two. CPRG three had minimal modifications made to its design at any time throughout the design process.

CPRG five had the largest proportion (33%) of group members focusing on only one design throughout the design process. CPRG four did not have anyone with a single design, while CPRG three had one participant. CPRG one and two had similar percentages of participants choosing to advance the design process with only one design.

Spatial and creative finding have been presented, separately, thus far. In the next section spatial and creative components are merged to establish correlations or trends among the data.

Spatial Results and Creative Elements

Male data indicated a correlation between creative product rank and spatial visualization tests PF and SD. The correlation between creative product rank and PF suggested a weak ($r_S = .24$), but significant ($p = .02$) relationship. Furthermore, the association between creative product rank and SD was moderate ($r_S = .33$) and significant ($p = .001$). However, there was no significant correlation between object manipulation assessments and CPRS among females. Though, there was a strong ($r_S = -.69$), but not quite significant ($p = .08$) inverse correlation between CPRS and the Revised PSVT: R score for females.

Narrowing the focus to those who scored a five on creative product rank revealed three very strong and significant relationships between spatial visualization assessments. The results are shown in Table 4.3 from an analysis performed by a Spearman's rank correlation test. Since no females scored a five on creative product rank, data provided by males and females cannot be compared.

The last finding suggested that acquiring visualization skills is not a guarantee, at the introductory level, that one will also produce creative products. Although, when spatial assessments are plotted against CPRS, as in Figure 4.5, those who scored high on creative rank tended to also score above 50% on the PF and SD assessments. FB score; however, does not indicate this trend.

The correlations and trends disclosed thus far offer an opportunity for an interpretation and discussion. The next section explores some aspects of the findings.

Discussion

The findings reported in Murray's Dissertation Chapter 2 suggest a difference existed in spatial ability among male and female introductory engineering majors according to the Revised PSVT: R assessment data. Previous studies (Maeda & Yoon, 2013; 2015) have also observed this phenomenon in the general population. The sub-sample; however, indicated no difference in the average Revised PSVT: R scores across genders. This is conceivable because the sample for this investigation is not one of the general population, but rather one that represents students with an interest in engineering. Furthermore, the sub-sample indicated females scored significantly lower on PF than males. This would suggest the sub-sample was not representative of the sample utilized in Murray's dissertation (2016) although they were drawn from the same pool.

Figure 4.6. shows graphical representations of CPRS vs. Revised PSVT: R score for the sub-sample used in this study for both genders. Although there are only seven data points for females, the data does suggest an inverse relationship between Revised PSVT: R score and CPRG. The only participants (male) to receive a CPRS of five also scored high on the Revised PSVT: R assessment. As previously indicated by Figure 4.4, no females scored high enough to be admitted to CPRG five. Does this imply females lag behind males in design creativity and spatial skills? Are females prohibited

from reaching higher levels of creativity due to lack of spatial skills? Neither of these questions can be answered by this study; however, they offer new avenues of investigation. Only 31 of the female students completed product designs to be analyzed in this study. Perhaps an increased participation would have uncovered a wider range of creative product and spatial skill among females.

When creativity was compared across genders, after ranking product designs on a five-point scale, the average scores were not significantly different. However, males scored higher and lower, at greater percentages, than females overall. Males with a CPRS of one typically did not follow directions and created objects that were not functional. For example, participants designed for six pads and several crayons, produced boxes with no creative feature, or submitted something that looked like a wad of paper and did not fully answer the open-ended questions. A few participants were openly honest and said they forgot about the assignment and created something at the very last minute. Females with a CPRS of one, on the other hand, tended to submit creative designs based on aesthetics instead of creative designs based on functional creative problem solving. Hence, they were thinking about solving the creativity problem with an out-of-domain technique. This was an interesting interpretation because participants identified creativity as the problem that needed to be addressed. Since their conception of creativity was more aligned with an artistic view, participants problematized creativity. In this case participants blended both artistic and engineering related conceptions of creativity into an engineering design task. Semantics played a role in how participants interpreted the design task.

Because the participants were enrolled as engineering majors they focused on acquiring engineering skills. Learning to master AutoCAD™, a tool used within the design and engineering domain, was the aim of the course participants were enrolled in. However, less than 30% turned in drawings prepared by AutoCAD™. Participants with high CPRSs were more likely to draw with AutoCAD™. This could suggest that AutoCAD™ helps individuals to visualize designs or that individuals with high visualization skills found AutoCAD™ to be an easy tool to utilize. Those who submitted hand drawings were able to depict appropriately scaled 2D and 3D images of product designs.

Those who forgot about the assignment, or did not pay attention to task details, may not have been motivated to carry out the project. Individuals can be enticed by different factors; some may be intrinsically motivated while others may be extrinsically motivated to engage in problem solving activities (Deci & Ryan, 1985). In addition, situational interest may have played a role in the particular task chosen for this assignment (Vroom, 1964). For instance, an industrial engineering major may be more motivated to reorganize “behind the scenes” processes at a Publix supermarket than design and build a physical product.

Also, participants may have been grade motivated. Another course may have needed more attention from a participant to increase a course grade. If that were the case, this particular assignment may have lost appeal, or vice versa if the participant needed to increase his or her grade in this course. In addition, the product design was assigned at the end of the semester. Students were aware of how much, or how little, effort they needed to expend in order to attain personal grade-related goals.

Participants who scored a five on creative product rank did not modify their designs and a third of those participants only progressed through the design process with one design. These participants had many ideas, in general, but once a design was chosen after sketching, they continued with the unaltered design through to completion. They did not make any mistakes that required modification or redesign. Although not consistent with typical design processes expert's use (Adams et al., 2011), this strategy worked for introductory engineer's on this simple design task. These students appeared to have the ability to visualize, with tools (AutoCAD™) or with internal (visualization) skills, to construct a product with no errors or modifications because it was planned well from the start.

Participants who constructed products with higher creative product rank also scores tended to have more ideas than those of a lower creative product rank. Lack of time and respect for generating ideas are known barriers to creativity (Basadur & Hausdorf, 1996; McCoy & Evans, 2002). Brophy (1998) suggests, in particular, that individuals with technical professions are more likely to overlook the value of ideation— the process of generating ideas. This study indicated most students recognized the benefit of ideation, but prematurely evaluated designs.

Ideation is central to the associative theory of creativity (Mednick, 1962). Ideas connected across domains have a tendency to be more creative because they draw upon diverse, but related ideas. The more remote the two ideas the more original the new idea will be (Acar & Runco, 2014). While participant ideas were not very remote, they did cross domains. Ideas largely came from other storage devices. The most creative products (Rank 5) combined multiple ideas into one overarching theme. For example, the middle picture under the title “Rank 5” on Figure 4.3 shows a Lazy Susan theme. The participant used the principle of rotation in combination with storage underneath and a snug fit for components. The Lazy Susan idea was elaborated upon to produce an original final product.

Summary

Three sub-research questions examined spatial skill, product and process creativity, and the integration of spatial and creative skills among first-year prospective engineers. Results of a Mann-Whitney U test revealed a difference between male and female participants on the PF assessment. Males performed significantly better than females. In addition, spatial visualization and the Revised PSVT: R assessments were significantly correlated with one another for males. Only SD-FB and SD-PF correlations were statistically significant for females.

When product creativity and elements of the design process were compared, four trends emerged. Participants with high CPRSs had a tendency to use AutoCAD™ and generate more design ideas. However, participants with a CPRS of five did not modify designs at any stage of the process. Consideration for only one design was typically observed by participants with products of rank five, two or one. Hence, high and low creative product rank scorers initially selected designs that they may or may not have modified through the design process.

Spatial and creative data were merged to determine relationships between the two data sets. Individuals (males) earning a CPRS of five had significant strongly correlated spatial visualization scores. PF and SD were significantly correlated with creative product rank for all males. No significantly correlated data emerged among female data; however, CPRS was negatively correlated with Revised PSVT: R scores.

Implications and Further Research

The discussion above presents more questions than answers to the research questions. Correlations and trends evolved from analysis and interpretation of the data. What is noteworthy is that female participants— those with an interest in engineering, tended to have lower average spatial scores than their male counterparts. How or why does this happen? What type of experiences have females had in comparison to males? Have females had equal access or opportunities to engage in spatial activities as well as those that promote creative problem solving? What specific factors contribute to why females do not have similar preparation as males at the time of entry into undergraduate programs in engineering? Could lack of formal introduction to spatial skills in education have something to do with gender difference?

Spatial skill development is not often a priority in U.S. K-12 schools (NRC, 2010) because assessments of verbal and mathematical skill level dominate high stakes testing. Perhaps an in depth look at male and female past experiences, across individuals with high and low spatial skill level, could explain the differences observed. A better understanding of how spatial skills develop can support an argument for the inclusion of spatial skill development at the K-12 level.

The lack of modifications to designs and the propensity to choose a design early in the design process may have worked for participants in this study, however it will eventually hinder progress on more complex problems. Isaksen and Treffinger (1985) explicate that divergent and convergent phases, within CPS stages, should adhere to specific ground rules. One tenet of divergent thinking is deferred judgment of ideas (Basadur, 1995). In practice individuals generate many ideas that may or may not be feasible for the specific problem. The point is that judgment is withheld until the convergent phase has begun. Off-the-wall ideas can spark other ideas which expand the possibilities. Avoiding hasty evaluation decisions is essential to convergent thinking. Adhering to these rules facilitates an open environment where alternatives may be considered and elaborated upon to produce creative solutions.

Quantity of ideas increases the possibility of quality ideas (Treffinger, Isaksen, & Stead-Dorval, 2005). Although participants had multiple ideas at the beginning of the design process they tended to fixate on one design without full consideration for alternatives that were drastically different (Jansson & Smith, 1991; Purcell & Gero, 1996). Participants with multiple designs were predominately elaborations of an original idea or modification(s) due to errors in construction.

Those with featureless box designs were generally designated to CPRG one or two because originality was lacking in comparison to the example unoriginal package given to students at the time the project was assigned (See Appendix A). Perhaps this was also a form of design fixation. Providing a picture in the absence of domain knowledge has been found to promote fixation (Purcell & Gero, 1996). If the picture had not been provided the participants may not have designed a package with a box-like shape. Even designs by participants with features may have been fixated by the shape.

Implications for educators include considerations for design instruction. The explicit use of ideation and divergent-convergent processes throughout the design process should be emphasized and make clear. Data showed that those who received high CPRSs did not do so because participants utilized a creative problem solving or design process method. In addition, instructors of design-based courses might consider emphasizing spatial visualization. Likewise, introductory courses in drawing should consider introducing the design process. Drawing possible design components occurs in the early stages of design and perhaps the focus could attend to the initial stages of design.

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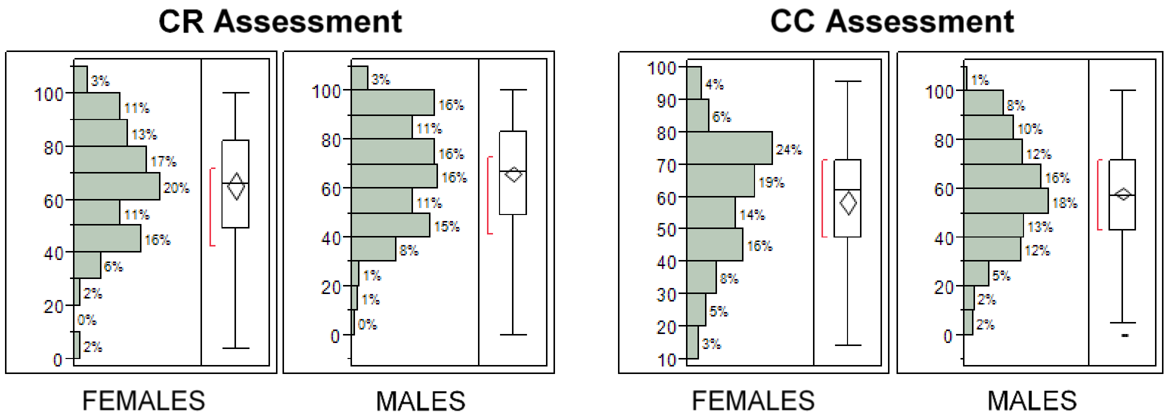


Figure 4.1. Mental rotations assessment results for females and males.

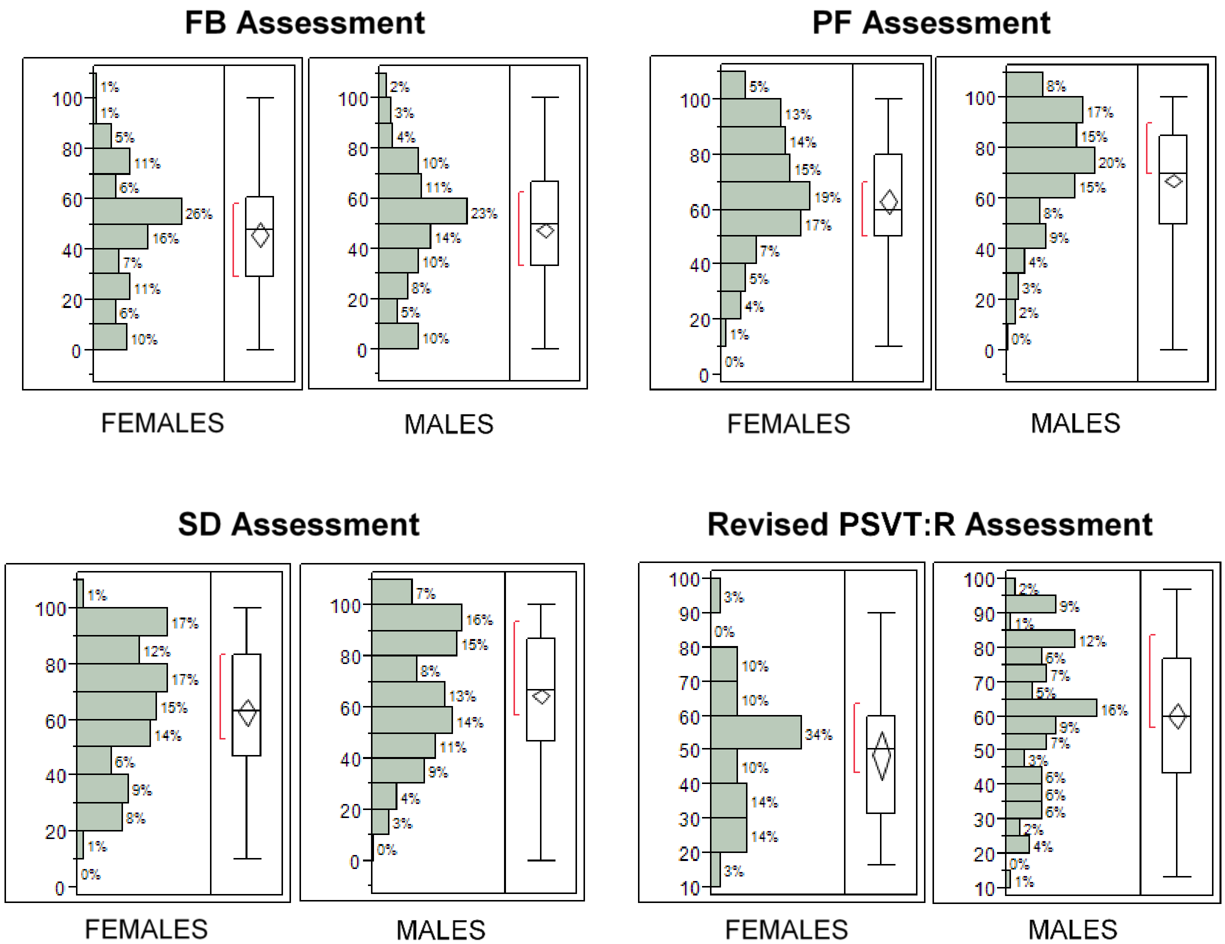


Figure 4.2. Spatial visualization assessment results for females and males.

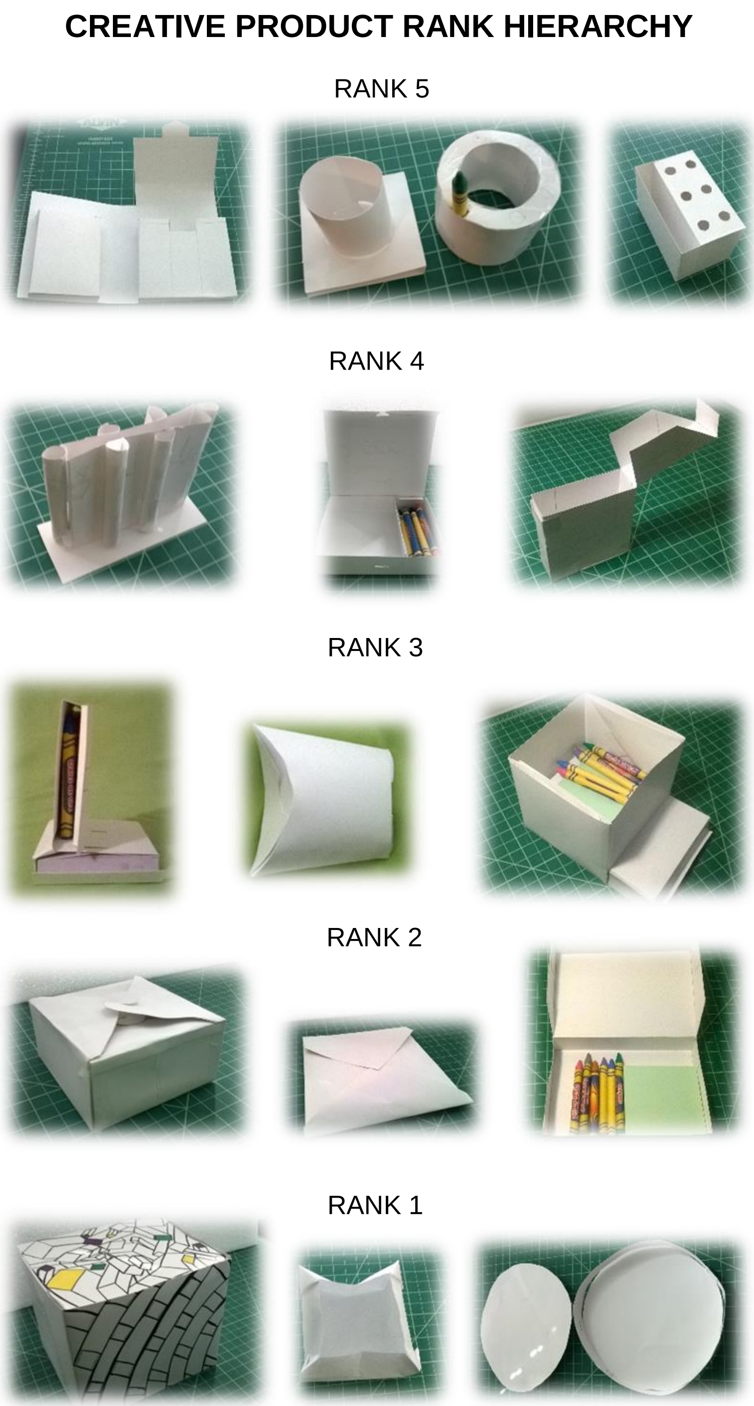


Figure 4.3. Example product designs assigned to creative product rank groups.

PRODUCT CREATIVITY RANKINGS

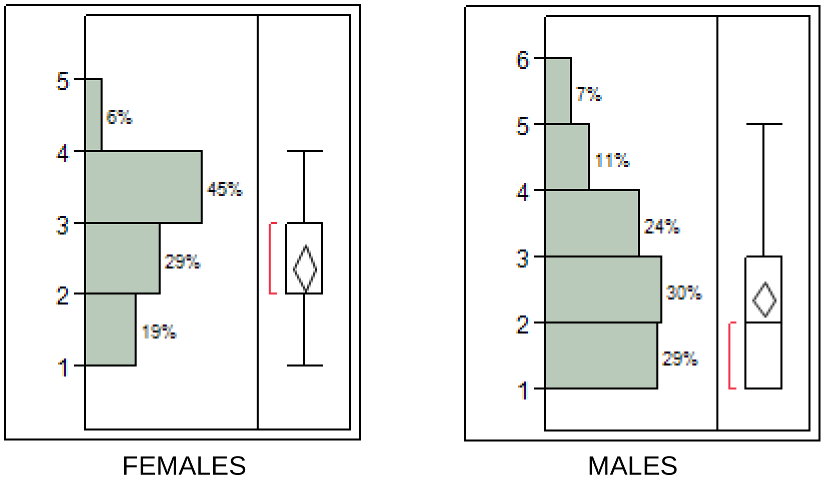
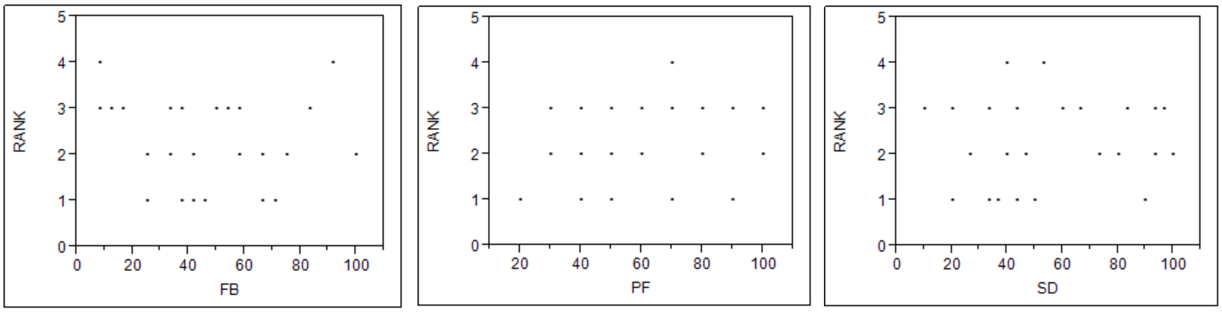
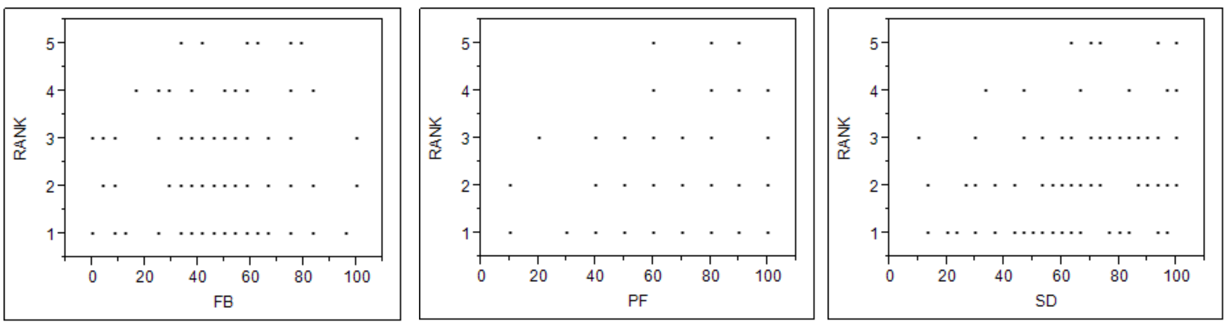


Figure 4.4. Creativity results for female and male participants.

CREATIVE PRODUCT RANK VS. SPATIAL VISUALIZATION



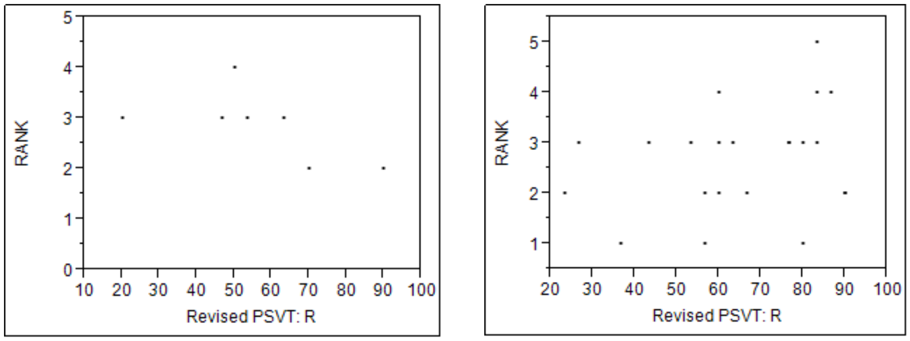
DATA GATHERED FROM FEMALES



DATA GATHERED FROM MALES

Figure 4.5. Creative product rank vs. spatial visualization score for females and males.

CREATIVE PRODUCT RANK VS. REVISED PSVT: R SCORE



FEMALES MALES

Figure 4.6. Creative product rank vs. Revised PSVT: R scores for females and males.

Table 4.1

Spearman's Rank Correlation Coefficient Matrix for the Sub-Sample

Measure	1	2	3	4	5	6
Females						
1. CR						
2. CC	.17					
3. Revised PSVT: R	-	.27				
4. FB	.24	.13	.57			
5. PF	.37	.30	.44	.29		
6. SD	.12	.36*	.74	.37*	.50**	
Males						
1. CR						
2. CC	.38**					
3. Revised PSVT: R	-	.38				
4. FB	.37**	.16	.68**			
5. PF	.27*	.38***	.68***	.39***		
6. SD	.38**	.36***	.76***	.54***	.57***	

*Note: *p < .05, **p < .01, ***p < .001*

Table 4.2

Mann-Whitney U-test Results for the Sub-Sample

	N	Median Rank	Sum of Ranks	Test χ^2	*p*	*d*
CR						
Male	66	45.2	2983	0.016	.899	0.072
Female	23	44.4	1021			
CC						
Male	90	58.7	5283	1.52	.218	0.191
Female	31	67.7	2098			
Revised PSVT: R						
Male	24	17	408	1.29	.267	0.457
Female	7	12.6	88			
FB						
Male	89	58.6	5308	0.039	.844	0.105
Female	30	61.1	1832			
PF						
Male	90	64.9	5843	4.49	.034	0.401
Female	31	49.6	1537			
SD						
Male	91	63.4	5772	1.07	.3	0.253
Female	31	55.8	1730			

Table 4.3

Percentage of Participants that Use a Process Component.

	Creative Product Rank Score				
Process Component	**5**	**4**	**3**	**2**	**1**
Modifications	0%	25%	6%	22%	16%
One Design	33%	0%	3%	14%	16%

CHAPTER 5

CONCLUSION

STEM in Policy

Preparing the Next Generation of STEM Innovators: Identifying and Developing Our Nation's Human Capital (NSF, 2010) is just one of many documents to advocate for science, technology, engineering and mathematics (STEM) education in the United States (U.S.). Since then the Committee on STEM Education of the National Science and Technology Council advanced the Federal STEM Education 5-year Strategic Plan (2013) disclosing President Obama's intention to reroute federal funding for the purpose of prioritizing STEM education. The plan included creating 100,000 STEM-ed teachers, providing money to the National Science Foundation (NSF) to award grants for research focused on STEM teaching and learning at the undergraduate level, and supplying the Smithsonian Institute with resources to partner with other national organizations to underscore STEM education in informal settings.

In addition to the above documents, the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013); the standards for U.S. K-12 science education, highlight mathematics, engineering, and technology requirements within the science and engineering practices. The NGSS state:

> Engineers' activities, however, have elements that are distinct from those of scientists. These elements include specifying constraints and criteria for desired qualities of the solution, developing a design plan, producing and testing models

> or prototypes, selecting among alternative design features to optimize the achievement of design criteria, and refining design ideas based on the performance of a prototype or simulation. (NGSS, 2013, p. 11)

The Accreditation Board for Engineering Technology (ABET); the agency that certifies post-secondary programs, also includes design. Criteria 3. (student outcomes), comprises the following standards:

b. an ability to design and conduct experiments, as well as to analyze and interpret data

c. an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability (ABET, 2016)

It is clear that the U.S. educational system recognizes the importance of STEM education at the K-12 and post-secondary level. Design seems to be the focus of the "E" in STEM. Like the scientific method, design is an iterative and recursive process and specific to the nature of the question or problem.

Sir Ove Arup, the famous architect and structural engineer, once said, "Engineering problems are under-defined; there are many solutions, good, bad and indifferent. The art is to arrive at a good solution. This is a creative activity, involving imagination, intuition and deliberate choice." The aforementioned statement imparts an important concept about engineering design; innovative design arises from creative problem solving (CPS). Designers who generate many ideas can select from a variety of options in an effort to construct a solution that satisfies specified needs. Ideation is generative and decision-making is evaluative. CPS begins with redefining the original problem and proceeds through an iterative process of generation and evaluation.

The National Academy of Engineering (NAE) in conjunction with the National Research Council (NRC) promote creativity in K-12 engineering education (NAE & NRC, 2009). They advocate three principles: an emphasis on engineering design, the integration of science, technology, engineering, and mathematics (STEM) components, and the adoption of engineering habits of mind. Creativity is considered a habit of mind and is the foundation of innovative engineering design.

Government reports state they see the potential in young people as opportunities to enhance the nation's capital through advancement in interdisciplinary activities. Individual's with "mathematical and spatial abilities alone or in combination with verbal aptitude, along with other factors such as creativity, leadership, self-motivation, and a diligent ethic" are known as potential STEM "innovators" (NSF, 2010, p. 6). The NSF also suggests those that do not advance into STEM fields would benefit from scientific, spatial, and quantitative expertise.

Purpose

This dissertation examined two skills important to the engineering community of practice (ECoP): spatial and creative skills. Student's spatial skills were characterized via scores on object manipulation assessments. Creativity in engineering was evaluated by interviews, written explanations of the design process, and product designs. The overall purpose of the dissertation was to understand what repertoires of practice students utilize as newcomers to the ECoP through the design of a package.

Eminent discoverers and inventors have attributed their discoveries and inventions in part to visualization (Brophy, 1998). Those who publish in STEM or have patents were found to have high spatial skills as K-12 students (Kell, Lubinski, Benbow, & Steiger, 2013).

Contributions

Overall the dissertation set contributes to the limited inquiry into domain-specific spatial and creative skills associated with the field of engineering. Chapter Two examined how assessments of object manipulation skills compared with one another and across gender. It appears females with an interest in engineering do not significantly differ from males on most object manipulation assessments. Differences only arise in the single assessment engineering schools choose to utilize to measure spatial skills: the Revised Purdue Spatial Visualization Test of Rotations.

Chapter Three explored what introductory prospective engineers know and think about creativity in engineering to understand their implicit theories of design creativity. Some participants believed creativity was purely aesthetic. Others viewed creativity as a balance between problem solving and aesthetics. And some equated creativity with problem solving. Participant conceptions of creativity as problem solving varied broadly and manifested differently in product designs. Different patterns of the design process emerged, but most selected a design from a couple of idea. Participants then sketched a design and constructed it. Divergent thinking skills were predominately used in the beginning stages of design.

Chapter Four integrated spatial and creative skill scores to investigate possible patterns among males and females. There were no significant differences in average creative scores between genders, but males did score at the highest levels while females did not. Males who scored high on creativity also scored above 50% on PF and SD assessments. In addition, high creativity scoring males had significantly strong correlations between spatial visualization scores (PF-SD, PF-FB, and FB-SD).

Implications

The findings imparted in this dissertation have implications for K-12 teachers, engineering instructors, and policy makers. Design and spatial skills are essential for engineering education. Policy documents related to STEM education include both; however, creativity and specific spatial skills have not always been emphasized. How are teachers going to know how to implement these skills at the K-12 and post-secondary level? Currently neither are emphasized in the K-12 curriculum.

Post-secondary faculty who teach introductory engineering courses should be made aware of student conceptions about engineering creativity. K-12 instruction connects creativity with art, not STEM. Thus students transfer what they know about creativity to STEM domains. This is problematic, but if these tacitly known assumptions are made explicit, students may be able to advance their understanding of the ECoP. In addition, the use of one spatial assessment for placement decisions should be reconsidered. Data shows females do not lag behind males on all object manipulation assessments. Knowing where students have difficulty directs appropriate interventions.

Lastly, policy makers ought to further deliberate on what specific facets of design and spatial skills for STEM and non-STEM related fields are important for students to know and understand at each academic level. A broad knowledge and skill set advances creativity, and in turn innovation, in many professional fields.

Future Directions

The three paper dissertation set uncovered more questions for investigation about student learning than provides answers. Both spatial and creative skill exploration could be expanded. Perspective taking, spatial perception, and disembedding are other spatial skills specific to STEM domains. How well formed are prospective engineers' spatial skills overall? Does experience with formal and informal science, technology, engineering, or mathematics strengthen these skills? The world we live in is three-dimensional, not two-dimensional. Hands-on activities might improve three dimensional skills. Often times, schools use two-dimensional representations of three dimensional structures, because the written word was originally placed on paper in books. Perhaps the notion of static three-dimensional objects depicted in a two dimensional space is problematic. Touching and manipulating objects could provide the visual experience necessary to understand how objects look in different orientations. Successive experience with physical three-dimensional object manipulation may offer enough tangible practice to advance internal visualization skills.

Furthermore, how do males and females, interested in pursuing engineering careers, perform on object visualization assessments in comparison to spatial visualization assessments? Kozhevnikov, Hegarty, and Mayer (2002) have illustrated that high visualizers are either spatial visualizers or object visualizer, but not both. Some students enrolled in engineering may be better at object visualization instead of spatial visualization.

What types of experiences have students had (both inside and outside of school) that attracted them to engineering? Did these experiences adequately introduce students to the practices of engineering? NGSS requires U.S. K-12 science teachers to teach engineering practices alongside science practices. Are students able to differentiate the two? Engineering practice has generally been introduced to K-12 students as a construction design challenge—a narrowly conceived view of the practice. Identifying students' previous experiences helps to understand how and why conceptions of engineering practice arise.

In addition, in what ways have students been introduced to creativity? Do students value creativity in design? In U.S. culture STEM fields are valued over the arts, related to possible career choices for young people. It is possible the conflation of creativity between art and STEM causes individuals to devalue creativity because of its association with art, not STEM. How do student views about creativity in engineering change during the first years of formal engineering education? The traditional engineering curriculum begins with engineering science courses that are conducted in lecture format. In upper level engineering courses students are more likely to design.

It is also of interest to determine teacher and instructor implicit theories of design creativity. Educator views guide how and what they select as learning experiences for students. If educators do not value creativity, then students will infer creativity is not important. Daly et al. (2014) revealed that students did not value creativity's importance, because it was not assessed. Even when instructors do believe creativity is important, they need to explicitly express this view to their students and they need to assess it.

Conclusions

We know little about what tools prospective engineers have and choose to use in design. Each individual's repertoire of practice (Rogoff et al., 2007) is different and influenced by membership and engagement in multiple systems— family, religious affiliation, school, social organizations, and communities of professional practice. These experiences contribute to individual's practice-linked identities (Nasir & Hand, 2008) which are depend on the particular social milieu (Lave & Wenger, 1991).

Knowledge of student understandings are essential to craft educative experiences (Dewey, 1938) that have the capacity to activate transformative experiences (Pugh, 2011)—events that change personal or conceptual conceptions.

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APPENDIX A

The Design Task

Package Design & Construction

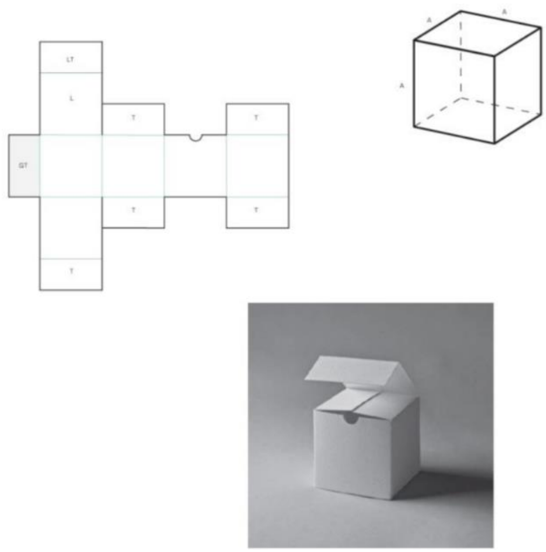

Figure 1. Simple cube box design.

Task

- Using the cardstock provided and your design skills, construct a ***creative*** and ***functional*** package intended to hold six crayons (blue, red, yellow, green, orange, and purple) and a stack of sticky notes (3 in x 3 in x ½ in). Figure 1 illustrates a simple functional design. There is nothing creative about this design. Yours should be creative.
- Record, in writing, how you went about designing the package. (Example: did you start with a sketch, by constructing it, or something else?)
- Construct a 2D (open package as shown above) and 3D drawing of your design.

What to Turn In:

1. 2D and 3D drawing of the package (can be drawn or produced by CAD)
2. Cardstock package creation (put your name on the bottom of the package)
3. Description of how you designed it: (There is no single answer here! We want to know your process.)
    - What was the inspiration for the design?
    - What elements were considered when designing the package?
    - Was one design envisioned and carried out to completion, or did you sketch or create several designs before selecting a final version? Elaborate, please.
    - Did you draw or create it first? Why?
    - What limited you in the design or construction of the package?

You may send your drawings, description, and questions to me as pdf documents. Please send to blank@gmail.com. I will also accept paper submissions.

APPENDIX B

Sample Semi-Structured Interview Questions

1. Please explain how you designed the final product. (Product and drawings available during the interview).
2. Ask about specific features of the design.
3. What, in your opinion, is the definition of “creativity”? Which fields of study are considered creative?
4. The design task included the requirement of functionality and creativity, how is your design functional? Please describe.
5. How is your design creative?
6. On a scale from one to ten, how would you rate the level of functionality of your design?
7. Why did you choose this level of functionality?
8. On a scale from one to ten, how would you rate the level of creativity of your design?
9. Why did you choose this level of creativity?
10. Have you decided on a specific engineering major yet? If so, which field have you chosen?
11. What was your motivation for choosing engineering as a major?
12. Do you plan to be an engineer? What do you want to specifically do as an engineer? Please elaborate.
13. Is there anything else you want to say about your design that you did not already share?